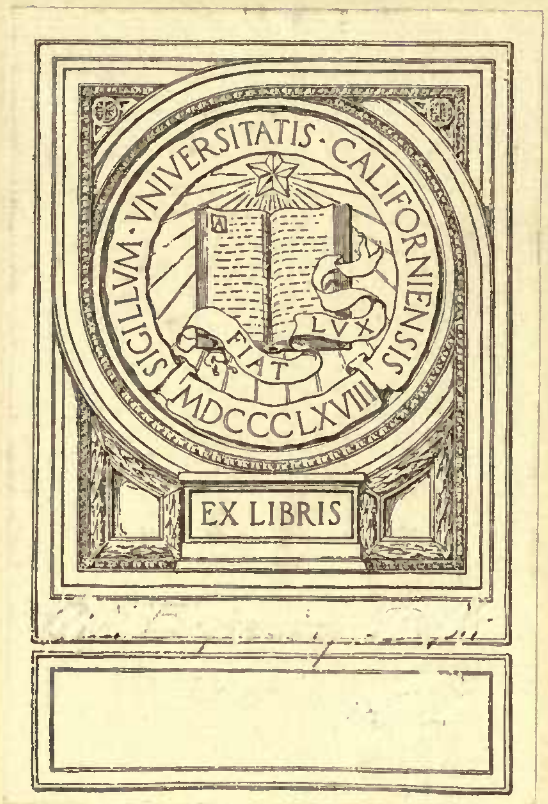
THE FORTH BRIDGE.

Reprinted from "ENGINEERING," February 28, 1890.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THE
FORTH BRIDGE.

Westhofen, W.

Reprinted from "ENGINEERING," February 28, 1890.

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APPENDIX.

THE FORTH BRIDGE.

By W. WESTHOFEN.

Historical.

It has at all times been a subject for controversy and a matter of difficulty to fix the precise boundary line between the river and the sea, that is to say exactly where the sea ends and the river commences. With regard to the Forth and its estuary, the same discussion has been carried on in Parliament and elsewhere with considerable warmth, but does not appear at the present moment to have got any nearer to settlement than in 1882. Taking, however, a point, say Anstruther, in Fifeshire, and another, say Dunbar, in Haddingtonshire, and drawing a line across which, roughly speaking, passes near the May Island and the Bass Rock, we may call it the Forth within and the sea without this imaginary boundary line. Starting westward from it we have 32 miles to Queensferry and 30 miles further to Stirling. On both sides of this great watershed are situated hundreds of square miles of some of the most fertile and best cultivated land in the three kingdoms. There are great coalfields, there is mineral wealth and, besides, an immense supply of food and other commodities which the inhabitants of these districts would wish to exchange or barter. But a serious barrier stood in the way, and stands even to this day, for the only means of intercommunication and of transport between the two shores is afforded by steam ferries or by sailing craft. Of the former there are three; the most seaward is that from Granton to Burntisland, five miles long, and 24 miles up the Forth; the next is that between South and North Queensferry, 32 miles from the boundary line; and the third at Kincardine, about 15 miles west of Queensferry. The first bridge for railway traffic is at Alloa, 20 miles from Queensferry, and the next at Stirling. The Granton-Burntisland passage (see map on the next page) is seriously affected by the weather in the winter months, is often impassable during strong gales, and at the best of times the disembarkation from train to boat and from boat to train is a source of considerable discomfort to passengers, and what is worse a great waste of time. The same holds good, though in a minor degree, at Queensferry and at Kincardine, and the traveller who requires to go from Dunbar to Anstruther, to put an extreme case, and who objects to either of the sea passages, has no choice left him but to go round by Alloa or Stirling, and to pass over about 150 miles of railroad, when the distance between the two towns mentioned is, as the crow flies, less than 18 miles. That under such conditions the commercial and agricultural intercourse and traffic between the eastern counties of Scotland suffered a serious check, and became reduced to a minimum, was but to be expected.

The same disadvantages existed in the case of all those travellers, bent on business or on pleasure, from north to south or *vice versâ*, who desired to pass through Edinburgh on their way, and who had either to cross by one of the ferries or make the long detour by Stirling, being in either case compelled to submit to a loss of valuable time. Finally, the principal railway companies whose systems are situated in the eastern and midland counties of England and the south of Scotland, could get no access to the northern parts of Scotland except by passing over the lines of a company whose interests were hostile and in opposition to their own. This brought about a most intolerable state of things, and is an easy explanation of the many struggles and attempts made by the East Coast lines to obtain a separate access to the counties north of the Forth. How great the necessity was of having means of communication between the two shores, and how largely even the inadequate provisions made hitherto were taken advantage of, is proved by the fact that in 1805—before a steamboat existed or a railroad was thought of—the right of running ferryboats between South and North Queensferry was let at a yearly rental of 2000*l.*, and it is stated in the Parliamentary evidence then taken that the revenue derived by outsiders who run goods and passengers across in yawls and small boats amounted to fully 5000*l.* per annum in addition.

It must be admitted that the Forth Bridge crosses the river at a point which leaves the eastern counties still somewhat in the same difficulty, but it reduces many of the local distances to be traversed by more than one-half, and the gain in time is considerable. Going by the Forth Bridge and its connecting lines the traveller will now be carried to and safely landed at Perth, Dundee, or Aberdeen, as the case may be, in a comparatively short time after leaving Edinburgh—in one and a quarter hours, one and three-quarter hours, and four hours respectively — independent of wind or tide and without difficulty and discomfort. In speaking of the new lines in connection with the bridge this matter will be further referred to.

The justification for the construction of so great a work must, however, be sought in the desire to serve larger interests than those of local traffic merely. In these days of high pressure, of living and working and eating and drinking at top speed, the saving of an hour or two for thousands of struggling men every day is a point of the greatest importance, and every delay, however excusable and unavoidable, is fatal to enterprise. Nor must the bridge be looked upon as a thing standing by itself, but rather as a portion—certainly a somewhat expensive portion—of a gigantic system of railway lines converging from all directions upon the capital of Scotland, affording means not only of more speedy and more comfortable travelling, but also giving facilities for the provision of a larger number of those through trains which are constantly becoming more necessary by the yearly addition of many miles of both main lines and branch lines. Altogether those concerned in this great undertaking are sanguine that within a very few months the courage, the foresight, and the wisdom of the directors of the Forth Bridge Railway Company, and of the other interested railway systems, will be fully proved by results which it is impossible to estimate even approximately just now.

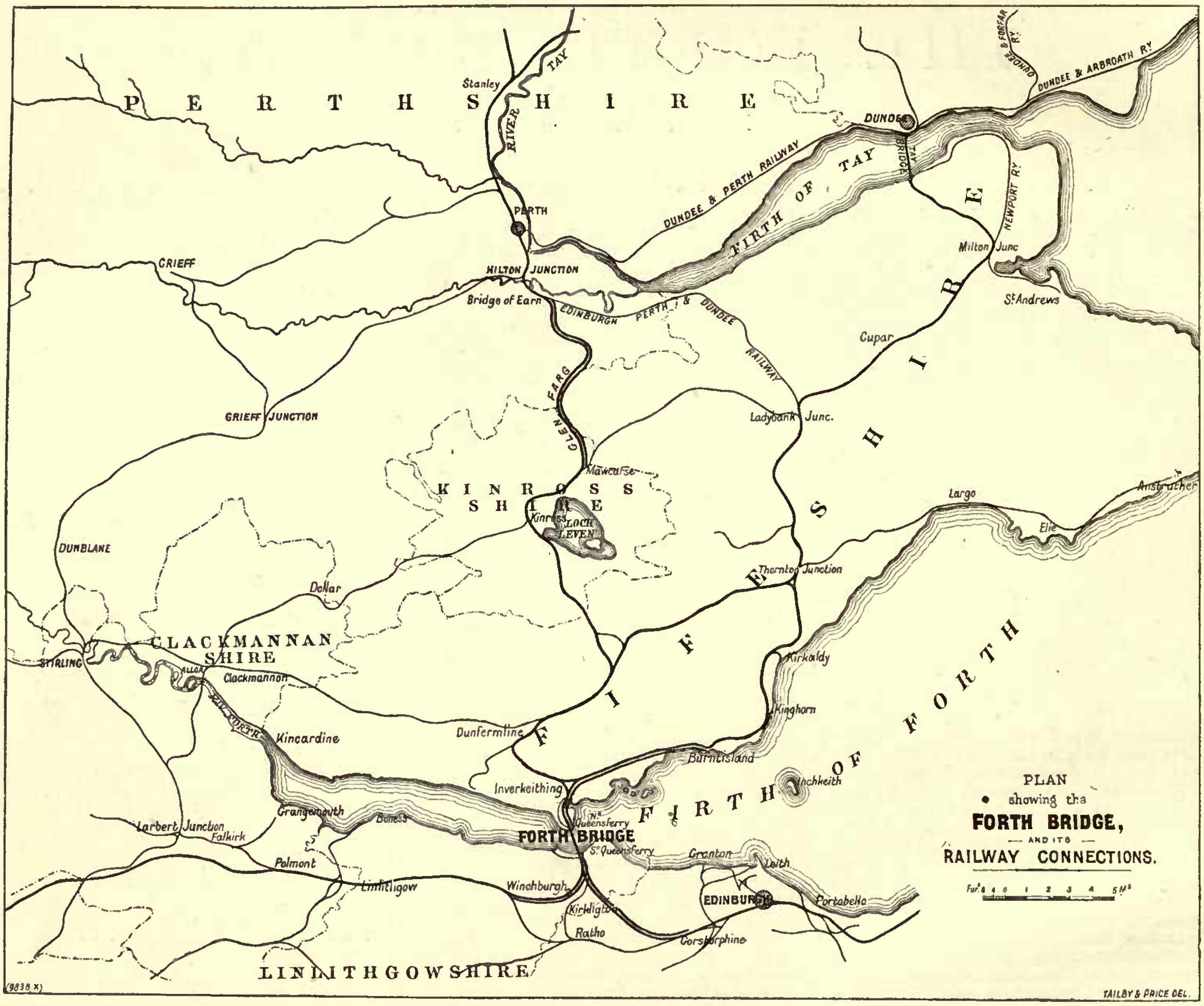
When and with whom the idea of bridging the Forth first originated is now a matter of pure conjecture. The Roman leader bent on exploration and conquest, probably conjured up in his mind's eye the faint outlines of a bridge as he trudged the weary miles along the south shore and found neither boats to carry him across nor ford to traverse—so must often have the sainted Margaret, the wife of Malcolm Caen-Mohr, on her frequent pious pilgrimages between Edinburgh, Linlithgow, and Dunfermline about the time of the Norman Conquest, and so probably her son Alexander the First of Scotland, who in attempting to cross from South to North Queensferry was overtaken by a gale and beaten down the Firth, and had finally to land on the island of Inchcolm, five miles away. He founded a priory on that island as a thanksoffering to Providence for a very narrow escape and in view of a warmer reception and more substantial entertainment should a similar misfortune again befall him. So must also many of the poor wayfarers who got drenched to the skin and suffered the horrors of sea-sickness during the crossing, and so must finally—if there was time for them to do so—the unfortunate party of people who were driven down the Hawes Brae at so rapid a pace that horses, carriage, and passengers went right off the pier into the water and none of them came out alive.

The idea thus floated through many minds until about 150 years ago, when a bridge was first spoken of, but particulars as to design, site, or probable cost do not seem obtainable.

In November, 1805, a proposal was made to construct a double tunnel—15 ft. wide and about the same in height—quaintly described as one for comers and one for goers—under the bed of the Forth, at some point to the west of Queensferry. The project was evidently seriously entertained, for in July, 1806, a prospectus was issued by "a number of noblemen and gentlemen of the first respectability and scientific character," inviting the public to subscribe—the shares being fixed at 100*l.* each. Further, in 1807, a pamphlet of about 120 pages was published in Edinburgh, entitled "Observations on the Advantages and Practicability of making Tunnels under Navigable Rivers—applicable to the proposed Tunnel under the Forth. Illustrated with a section and map." Nothing, however, seems to have come of the project, whether owing to difficulties of construction or of financing is not known—most probably both.

Within eleven years another effort was made, and we come upon a pamphlet entitled "Report relative to a Design for a Chain Bridge thrown over the Firth of Forth at Queensferry. . . . . By James Anderson, civil engineer and surveyor, Edinburgh, 1818." There were three elevations, differing as to height and length of clear span, but all equally bold and equally primitive; we give on the next page but one a reproduction on a smaller scale of the diagrams accompanying this report. The site was to have been nearly the same as that of the present bridge, starting from the same point at North Queensferry, passing very nearly over the centre of Inchgarvie, and terminating on the south shore about one-third of a mile east of the Hawes Pier, joining the Edinburgh Road just under Mons Hill. The clear height above high water was to have been either 90 ft. or 110 ft., the main spans 1500 or 2000 ft., the width for carriage road and footpath 33 ft., and the cost 175,000*l.* or 205,000*l.* The time required for completion was stated to be four years. A revenue of 10 per cent. on the capital expended was considered a very moderate estimate, which proves that the art of writing a highly coloured prospectus is of older date than most people would have thought. To judge by the estimate the designer can hardly have intended to put more than from 2000 to 2500 tons of iron into the bridge, and this quantity distributed over the length would have given the structure a very light and slender appearance, so light indeed that on a dull day it would hardly have been visible, and after a heavy gale probably no longer to be seen on a clear day either.

This scheme also proved abortive, and for forty years more the travelling public put up with what they could get, but at last in 1860 the North British Railway fixed upon a site about six miles to the west of South Queensferry as suitable for the construction of a railway bridge. The bridge was to have consisted of a number of large spans of 500 ft. each in the centre, with approaches in shorter spans at either end. The exact centre line was to have been from a point near Blackness Castle on the south shore to Charleston on the north shore, and connecting lines from near Linlithgow, on the Edinburgh and Glasgow line on the one side, and from Charleston to Dunfermline on the other side, would no doubt have established a very good through line to the north. Borings were taken and other investigations made. A design had been drawn out by Sir Thomas (then Mr.) Bouch, and Parliamentary powers for the construction of the bridge were obtained by an Act in 1865. The river here is about $2\frac{1}{2}$ miles wide, and the greatest depth of water about 60 ft.—but the bottom is loose and uncertain, and it was decided to build up and sink an experimental pier before proceeding further. But troubles intervened, and during the re-arrangement of the North British Railway Company in 1866-1867, the project was abandoned through various causes. For it were substituted improvements in the Queensferry passage by the construction of the railway slips at North Queensferry and Port Edgar. It was at first intended to have swinging landing-stages at each end, rising and falling with the tide—the trains by means of these to be run on and off the ferry steamers. The latter portion of the scheme was not carried out however, owing to the insufficient depth of water and the gradual silting up near the piers, which necessitates the periodical assistance of dredgers to keep a channel clear, although the ferry steamer draws little more than $4\frac{1}{2}$ ft. of water. These conditions are a source of much discomfort to the passengers by this route—for the light draught steamer can hardly hold its own against a gale of wind broadside on, and many people become seasick during a passage lasting at the worst of times barely twenty minutes.



In 1873 the Forth Bridge Company was formed for the purpose of carrying out the design by Sir Thomas Bouch of a suspension bridge with two large spans of 1600 ft. each. The capital was raised by the four principal railway companies interested in the East Coast traffic—namely, the Great Northern, the North-Eastern, the Midland, and the North-British, and the companies came to an understanding among themselves that they would between them send so much traffic across the bridge as would suffice to pay a dividend of 6 per cent. per annum on the contract sum. The Act authorising the construction of the bridge was passed in the same year, 1873, and a contract signed with Messrs. W. Arrol and Co., of Glasgow. An illustration showing elevation and plan of Sir Thomas Bouch's design is shown in Fig. 2. The central towers from which the main chains are suspended were to have been 550 ft. above high water, while the rail level would be at such height as to leave a clear head-room of 150 ft. above high water between the piers. The central tower on Inchgarvie was over 500 ft. long, which brought the foundations upon the sloping rock down to a depth of over 110 ft. below high water. There were two lines of rails carried at a distance of 100 ft. from each other, each line being supported on a pair of strong lattice girders, and these were laterally stiffened by single diagonal bracings reaching from side to side. The piers at Queensferry and on Fife were very nearly in the same position as those of the present bridge, and there were two approach viaducts to reach the high ground upon either side. The bridge was to have been constructed entirely of steel.

Offices and workshops—which are now standing—were built at Queensferry, and extensive brickworks near Inverkeithing laid out and started. A brick pier—one of eight, which were to form the base of the great Inchgarvie tower—was built at the extreme north-west corner, after a foundation stone had been laid with great ceremony. But the collapse of the ill-fated Tay Bridge in December, 1879, stopped the further progress of the work, and the investigations into the causes of that disaster, and the disclosures made, shook the public confidence in Sir Thomas Bouch's design, and rendered a thorough reconsideration of the whole subject necessary. As a first result of this, the suspension bridge was abandoned, and the four railway companies above named instructed their consulting engineers—Messrs. Barlow, Harrison, and Fowler—to meet and consider the feasibility of building a bridge for railway purposes across the Forth, and assuming the feasibility to be proved, to decide what description of bridge it would be most desirable to adopt. It was fairly well known how many types of bridge there were to select from for such a site; these were (1) Mr. Bouch's original design (Fig. 2); (2) three forms of suspension bridges with stiffening guides and braced chains (Fig. 3); and (3) a cantilever bridge (Fig. 4). The inquiry was most comprehensive. It embraced not only bridges as set forth, but also tunnels, and both of these for different sites.

With regard to tunnels, it was considered that

the great depth of water in the two main channels —above 200 ft.—and the high ground upon both shores, would necessitate very steep gradients and long approaches—making the tunnel many miles long, irrespective of the uncertainty of the nature of the ground through which the tunnel would have to be cut.

All things considered, the most suitable site for a bridge was held to be that at Queensferry; and, owing to the great depth of water and the nature of the bottom of the estuary, it was not considered expedient to construct a bridge with shorter spans than those which are indicated by the natural configuration of the ground.

The original design for a continuous girder bridge (see Fig. 4)—on the cantilever and central girder principle which had been submitted by Messrs. Fowler and Baker—was in some particulars modified to suit the conflicting views of the other consulting engineers, and was then submitted to the directors in May, 1881. After consultation with the officers of the Board of Trade, this design (see Fig. 5) was finally adopted, and Messrs. Fowler and Baker were appointed engineers to carry it into execution.

In July, 1882, an Act of Parliament was obtained, authorising the construction of the bridge, and sanctioning the new financial arrangement by which the capital of the Forth Bridge Company was guaranteed with interest at 4 per cent. per annum, each of the four contracting railway companies undertaking to find its share of the capital expenditure and pay its share of the interest. It is also agreed that the North British Railway Company will maintain the per-

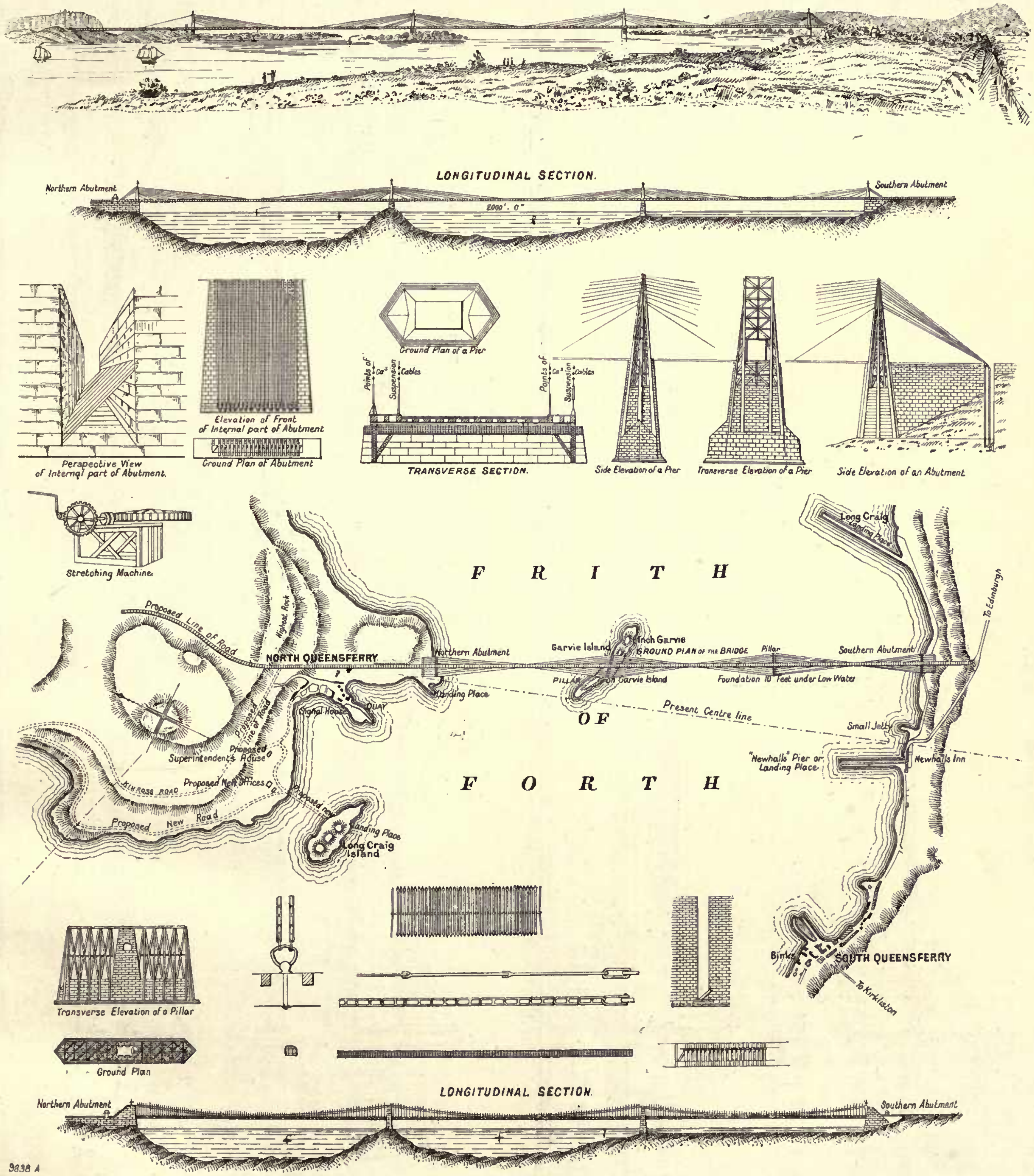
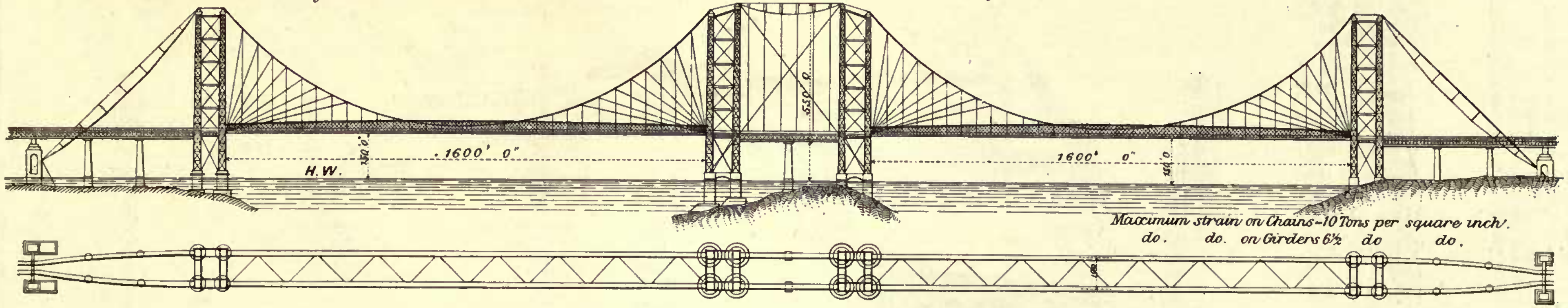


FIG. 1. ANDERSON'S DESIGN FOR BRIDGE OVER THE FORTH, 1818.

ALTERNATIVE PRELIMINARY DESIGNS FOR THE FORTH BRIDGE.

Fig. 2.

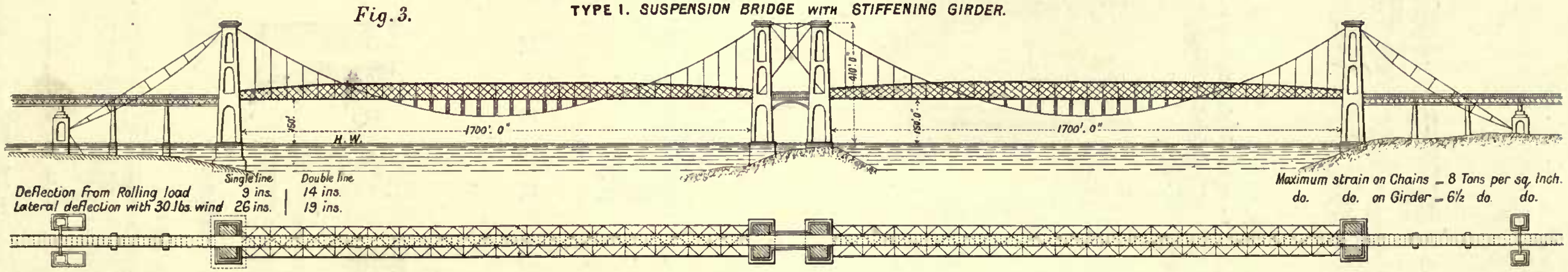
FORTH BRIDGE *Designed by Sir Thos. Bouch & Contracted for by Mess.rs Arrol*



Maximum strain on Chains – 10 Tons per square inch.
do. do. on Girders 6½ do do.

Fig. 3.

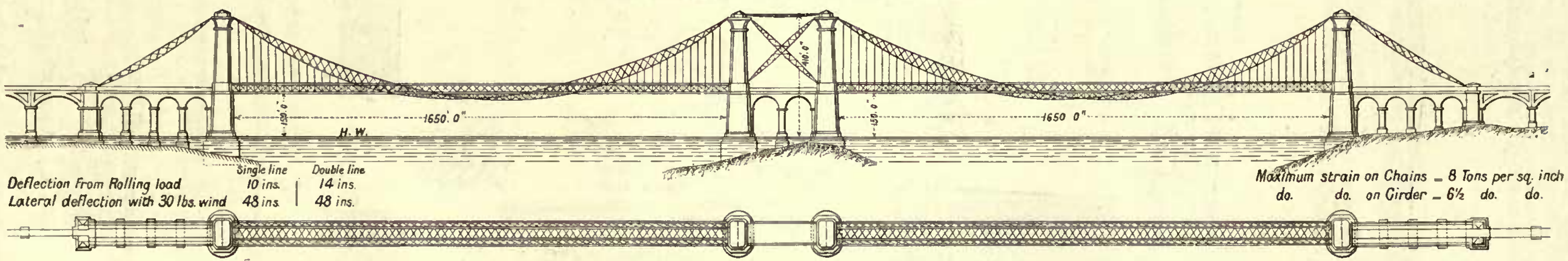
TYPE 1. *SUSPENSION BRIDGE WITH STIFFENING GIRDER.*



	Single line	Double line
Deflection from Rolling load	3 ins.	14 ins.
Lateral deflection with 30 lbs. wind	26 ins.	19 ins.

Maximum strain on Chains – 8 Tons per sq. inch.
do. do. on Girder – 6½ do do.

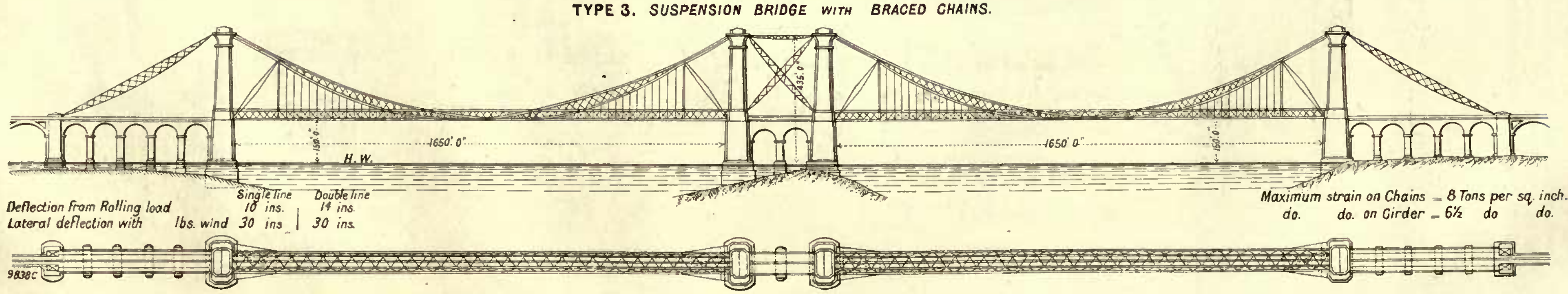
TYPE 2. *SUSPENSION BRIDGE WITH BRACED CHAINS.*



	Single line	Double line
Deflection from Rolling load	10 ins.	14 ins.
Lateral deflection with 30 lbs. wind	48 ins.	48 ins.

Maximum strain on Chains – 8 Tons per sq. inch
do. do. on Girder – 6½ do. do.

TYPE 3. *SUSPENSION BRIDGE WITH BRACED CHAINS.*



	Single line	Double line
Deflection from Rolling load	10 ins.	14 ins.
Lateral deflection with lbs. wind	30 ins	30 ins.

Maximum strain on Chains – 8 Tons per sq. inch.
do. do. on Girder – 6½ do do.

THE FORTH BRIDGE, CANTILEVER TYPE; ORIGINAL AND FINAL DESIGNS.

MESSRS. HARRISON, BARLOW, FOWLER, AND BAKER, ENGINEERS.

Fig. 4.

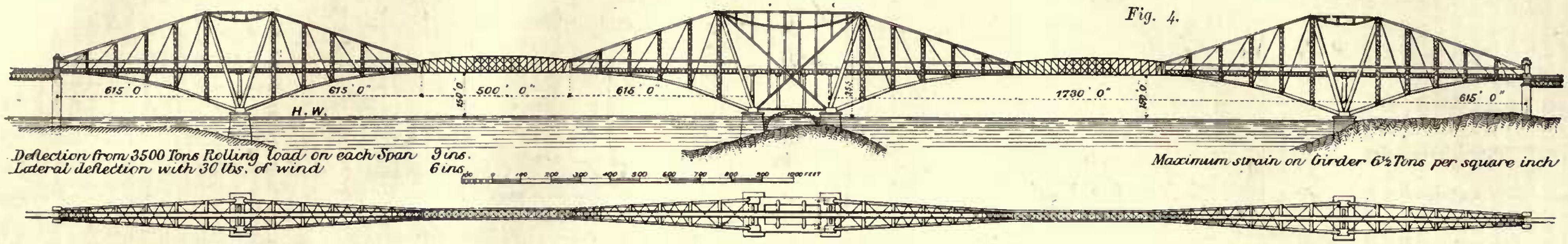
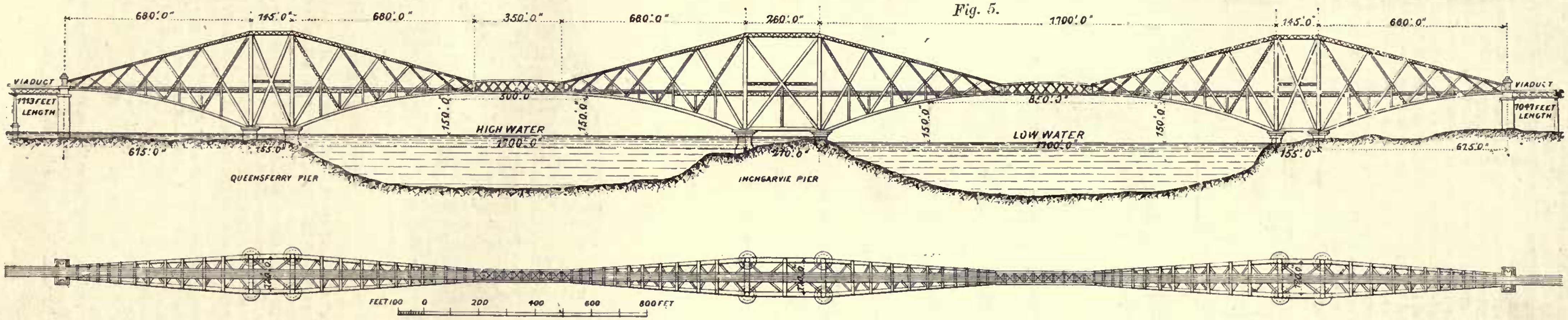


Fig. 5.



manent way on the bridge, and conduct and manage all traffic, while the Forth Bridge Railway Company undertakes to keep the structure generally in repair and good order.

On Cantilever Bridges Generally.

Some little confusion of thought would appear to exist in many minds as regards this type of construction. Most people are willing to concede the antiquity of the arch and of the suspension system, but are doubtful whether the "continuous girder," if it be rechristened "cantilever and central girder," be not a modern and patentable invention. As a matter of fact, it is a pre-historic arrangement. In the earliest Egyptian and Indian temples will be found the stone corbel and lintel combination shown in Fig. 6 (see next page), and in the oldest, as in the most modern, wooden bridges will be seen practically the same thing in timber (Fig. 7).

Skeleton bridges on a similar principle have for ages past been thrown by savages across rivers. A sketch of one such on the route of the Canadian Pacific Railway is given in Fig. 8. Perhaps one of the most interesting structures of this kind ever built is a bridge in Thibet, constructed about 220 years ago, and illustrated by Fig. 9.

This sketch is reproduced from a drawing made in 1783 by Lieutenant Davis, R.N., who formed part of the embassy to the Court of the Teshoo Lama in Thibet, an account of which with illustrations was published in London in the year 1800. The book was a popular one at the time, and was translated and republished in Germany, so that both English and German engineers had the opportunity eighty years ago of reading the following, probably the first, description of a "cantilever and central girder" bridge ever published. "The bridge of Wandipore is of singular lightness and beauty in its appearance. The span measures 112 ft.; *it consists of three parts, two sides, and a centre nearly equal to each other*, the sides having a considerable slope raise the elevation of the centre platform, which is horizontal, some feet above the floor of the galleries. A quadruple row of timbers, their ends being set in the masonry of the bank, and the pier supports the sides; the centre part is laid from side to side." Making allowance for difference of material the preceding work may fairly be looked upon as the prototype of the proposed Forth Bridge.

Descending to more recent times, it will be found that the term "cantilever and central girder" has ever been familiar as a household word to all educated engineers, because in treating on the strains in continuous girders it has almost invariably been the rule of authors to regard the structure as a central girder suspended from two cantilevers at the points of contrary flexure. Thus writing in 1850 on the Britannia Bridge, Mr. Edwin Clark premises severing the beam at the point of contrary flexure, and suspending the central portion from the "semi-beams or cantilevers," and appends the diagram (Fig. 10) in illustration of the resultant strains.

He also gives a sketch (Fig. 11) of "a shorter tube resting on brackets from the pier at either extremity, as below," which had been discussed by Mr. Stephenson in 1846.

In the former year also Sir John Fowler not only talked about severing the beam at the point of contrary flexure and suspending it, but had the experiment tried with a large wooden model, and the result was recorded in the discussion on the Torksey Bridge (Min. Proc. Inst. C.E., vol. ix., page 256).

In 1855 Mr. Barton, in a paper on the Boyne Viaduct (Min. Proc. Inst. C.E., vol. xiv., page 457), pointed out that the points of contrary flexure might be made to coincide with any previously determined points by severing the beam, and he added this most suggestive comment: "In very large spans where it may be a matter of great importance to reduce the weight in the middle of the beam as much as possible, the quantity in material in the top and bottom tables, as well as of the sides, may be reduced to a minimum by throwing the points of contrary flexure towards the middle of the beam, the great weight of material being placed over the piers." This is exactly what has been done in the Forth Bridge girders.

In 1858, Mr. Latham, in his well-known work on wrought-iron bridges (page 222), also speaks of "a girder suspended from the cantilever girders," and in 1859 Mr. W. H. Barlow took out a patent with reference to that and other matters. He preferred making the depth at the pier 1½ times the depth at the centre. In the Forth Bridge the ratio will be 7 to 1 instead of 1½ to 1.

In 1862 Professor Ritter, of Hanover, in his justly popular work "Dach-und-Brucken Constructionen" (Chapter X.) again drew attention to the fact that "hinges can be employed with advantage in girder bridges;" that a "great saving of material is effected by using a continuous girder and breaking the continuity by means of hinges." To enforce his conclusions he works out in full detail the stresses upon all of the members of a continuous girder bridge of 160 metres, or, say, 525 ft. span of the type shown by Fig. 12.

In 1864 Mr. Fowler and Mr. Baker designed a steel bridge of 1000 ft. span on the said system for the proposed South Wales and Great Western Direct Railway Severn Crossing, but the span was subsequently reduced to 600 ft. An Act was obtained for the construction of the bridge, and the contract was let; but, owing to financial difficulties, the work was not proceeded with.

In 1867 Mr. Baker enforced the economical advantages of the continuous girder of varying depths in a series of articles on "Long Span

Bridges" (ENGINEERING, vol. iii.) which went through three editions in this country, were republished at Philadelphia, and translated into German and Dutch, and published in the Transactions of the Austrian and Dutch engineers respectively.

In 1871 Mr. Fowler and Mr. Baker made designs and estimates for a bridge across the Severn, comprising two girder spans of 800 ft. each, and in 1873 Mr. Baker, at the request of the Corporation of Middlesbrough, designed the superstructure for a proposed ferry bridge across the Tees, which included a 650 ft. span on the same system (ENGINEERING, vol. xvi., page 60).

In 1876 nine competitive designs were submitted for the proposed New York and Long Island Bridge, comprising one span of 734 ft. and one of 618 ft., and of these three designs, two were on the aforesaid system (Figs. 13 and 14). The first was that of the Delaware Bridge Company, and the second of Colonel Flad, the very able engineer who, under Captain Eads, carried out the great St. Louis steel arch bridge.

In the same year was built the first, and, so far as we know, the only railway bridge of the type under discussion (Fig. 15.) This is a bridge of 148 ft. span across the Warthe, near Posen. It might appear strange at first that the application to railway purposes of so well-known a system should have been deferred until 1876, but the explanation is that there are thousands of bridges in existence on the continuous girder, or in other words cantilever and central girder principle, but engineers as a rule have elected not to sever the bridge at the point of contrary flexure, or to make the girders of varying depth.

A glance at the annexed illustrations and description will satisfy our readers that there is nothing novel or untried in the principle of the structure designed for the Forth crossing. The reasons dictating the design in the case of the Forth Bridge are those which probably influenced the Red Indians in making the structure illustrated by Fig. 8—economy of material and facility of erection. It must be conceded, however, that except as regards principle the design is essentially novel, but the novelties are dictated by the unexampled size of the structure, and are due simply to the perfect adaptation of the principle of the continuous girder and the general laws regarding the strength of materials to the special conditions of the case. Thus it will be observed that the structure is a continuous girder of varying depth on plan as well as elevation, the central girder portion being of the ordinary width required for a double line of rails, and the cantilevers spreading out to an extreme width of 120 ft. at the piers. By this means the stresses on the horizontal bracing from wind pressure are much reduced, and lightness and compactness are attained. To further the same ends the whole of the vertical members are made of two struts inclined towards each other from base to summit and braced together. To reduce the extreme height of the structure, and bring the centre of gravity as low down as possible, the bottom members of the continuous girder are curved, springing from solid masonry piers at a height of 18 ft. only above high water, whereas in the design for the suspension bridge the main chains, carrying of course all the weight, were supported at a height of 550 ft. above the same point! The main compression members are steel tubes ranging up to 12 ft. in diameter, the tubular form being adopted for two reasons, firstly, because experiments have shown that inch for inch the tubular form is stronger than any other, and, secondly, because the amount of stiffening and secondary bracing is thereby reduced to the lowest percentage. It might be thought that columns 350 ft. in length were an untried novelty, but this is not so, as we have the precedent of the Saltash Bridge oval tubes 16 ft. 9 in. by 12 ft. 3 in. in diameter and 460 ft. in length, the strain upon which under the test load was higher per square inch than will be that on the steel columns of the Forth Bridge. The central girder portion is simply an ordinary double-line railway bridge of 350 ft. span with girders of a type intermediate between the girder of parallel depth and the bowstring. This is an economical type, and many Continental bridges have been so constructed.

When lecturing some years ago, Mr. Baker, with a view of presenting in a form easily understood and popularly remembered, a simple diagram of the manner in which the principal stresses of a cantilever bridge are distributed, devised the following arrangement of a human cantilever, or a living model of the Forth Bridge. (See Fig. 15A.)

Two men sitting on chairs extend their arms, and support the same by grasping sticks which are butted against the chairs. There are thus two complete piers, as represented in the outline drawing above their heads. The central girder is represented by a stick suspended or slung from the two inner hands of the men, while the anchorage provided by the counterpoise in the cantilever end piers is represented here by a pile of bricks at each end. When a load is put on the central girder by a person sitting on it, the men's arms and the anchorage ropes come into tension, and the men's bodies from the shoulders downwards and the sticks come into compression. The chairs are representative of the circular granite piers. Imagine the chairs one-third of a mile apart and the men's heads as high as the cross of St. Paul's, their arms represented by huge lattice steel girders and the sticks by tubes 12 ft. in diameter at the base, and a very good notion of the structure is obtained.

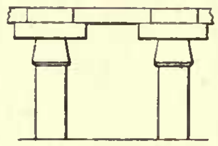


FIG. 6.

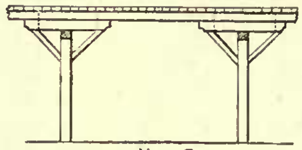


FIG. 7.

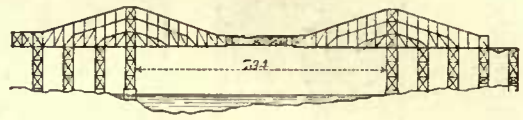


FIG. 13

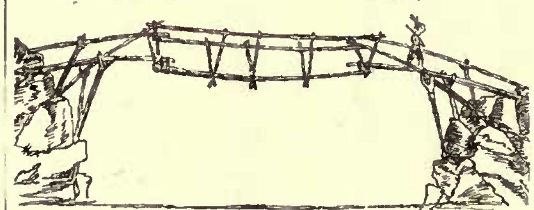


FIG. 8.

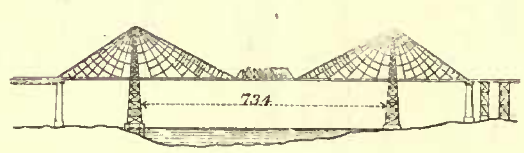


FIG. 14.

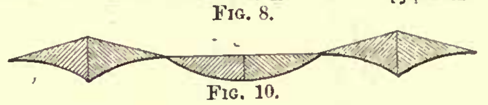


FIG. 10.

FIG. 11

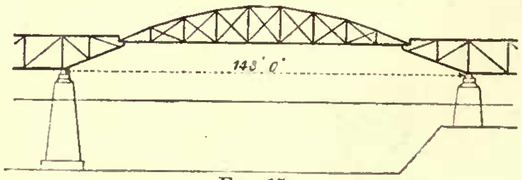


FIG. 15.

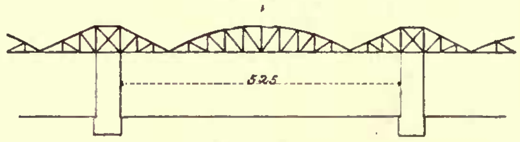


FIG. 12.

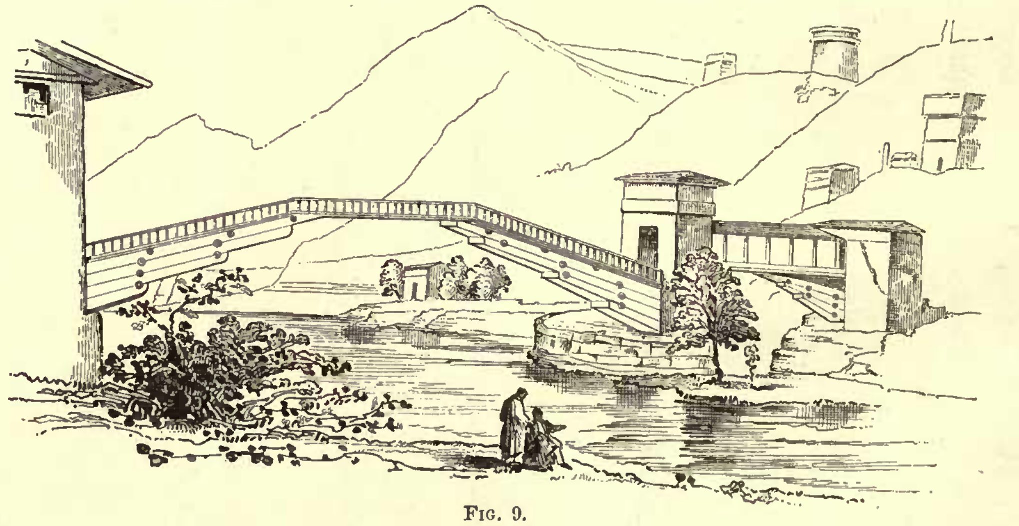


FIG. 9.

TYPES OF CANTILEVER BRIDGES.

The chief desiderata in the Forth Bridge, which is the largest railway bridge ever yet built, were clearly as follow:

1. The maximum attainable amount of rigidity, both vertically under the rolling load and laterally under wind pressure, so that the work when completed may by its freedom from vibration gain the confidence of the public, and enjoy the reputation of being not only the biggest and strongest, but also the stiffest bridge in the world.

2. Facility and security of erection, so that at any stage of erection the incomplete structure may be as secure against a hurricane as the finished bridge.

3. That no untried material be used in its construction, or in other words that no steel be employed which would not comply with the requirements of the Admiralty, Lloyd's, and the Underwriters' Registry, as determined by the experience gained in the use of many thousands of tons of steel plates, bars, and angles for shipbuilding purposes.

4. That the maximum economy be attained consistent with the fulfilment of the preceding conditions. We think it will be apparent to most engineers and bridge builders that the original suspension-bridge design complied with none of these conditions, whilst the girder design complies with all.

Of the present design it may be truly said that all anticipations have been most brilliantly realised, and its merits can now, in the light of practical experience, and of actual facts, be more easily pointed out. In the first instance the distribution of weight not only offers the advantage of having the greatest proportion, nearly one-fourth of it, immediately over the main supports, where it is most easily erected, but it offers in those places where the wind pressure would act with the greatest amount of leverage, the least amount of surface to act upon. Thus, while in the central tower of the Inchgarvie pier, the most exposed to storms, the weight per foot run is 23 tons, and in the first bay of cantilevers 21 tons, in the central girders of 350 ft. length it is only a little over 2 tons per foot. In a similar manner the structure decreases rapidly in height and breadth of girders, as it extends from the massive central towers towards the extremities of the cantilevers. Again, for purposes of erection every portion of the structure, as put in position, offered itself as a staging for carrying operations further

ahead, or afforded every means of suspending temporary staging from it. The greater portion of the work as erected could be securely fixed at once and rivetted up, and this close up to places where new parts were in course of erection. Great rigidity was thereby insured, and less temporary work required than in any other mode of construction, while it gave confidence to the workmen engaged, and offered every facility in providing for their safety, and for that of the structure itself.

Great stability is obtained by straddling the sides of the structure, as viewed in cross-section—that is, making it considerably wider at the base than at the top. In the central towers, the width at the base is somewhat more than one-third of the height, and a uniform batter is maintained throughout the structure. This feature conveys a sense of great security against the action of violent gales tending to overturn the bridge. Finally, the arrangement of cantilevers and central girders admits of the simplest and most effective form of expansion-joint, and this problem is solved here in the happiest manner, as will appear from the detailed description given later on.

On December 21, 1882, the contract for the construction of the Forth Bridge was let to the firm of Tancred, Arrol and Co. Both the contract sum and the time specified, have been exceeded, for reasons which will be fully apparent to the reader who follows attentively the development of this work, and who gives intelligent consideration to the conditions under which it had to be carried out.

Site of Bridge and Profile on Centre Line. Surrounding Country.

The site which was finally fixed upon as the most suitable in all respects for carrying the bridg across, is in its natural features singularly well adapted for that purpose. The general level of the country on both sides of the Firth lies at about the height at which it was required to carry the rails in order to afford sufficient headroom for the largest vessels in the Navy or merchant service. Should the project of making a ship canal between the Forth and Clyde—lately brought to the notice of the public—ever be carried into execution, and should the Forth thus become an international highway, as well as one of the finest natural harbours of refuge in the world, the largest vessel yet built would have to do no more than strike its topmasts should it happen to pass at the hour of high water of an extra high spring tide.

The river bottom, in all places where the foundations of piers had to be laid, consists of either the hard whinstone rock or of hard boulder clay, both of great soundness and solidity. At no point where foundations had to be placed is there a greater depth of water than that well within the capabilities of sinking caissons by pneumatic process. The only contraction in nearly 50 miles of river is to be found here, and it reduces the width, elsewhere never less than fully two miles to one mile and about 150 yards. (See Fig. 16.) On the North or Fife shore, a rocky promontory, somewhat triangular in shape, projects southwards for fully a mile and a quarter into the river, and affords not only sound building material in its bedrock, but also sheltered corners for discharging vessels and anchorages for a small fleet of barges and launches connected with the works. From the apex of this promontory, nearly due south, the small island of Inchgarvie lies distant exactly one-third of a mile, and between the two runs the Main or North Channel with a depth of over 200 ft. This is the channel almost exclusively used by shipping, because it is safer and easier to navigate than the South Channel, and also because it is the shorter road of the two. Inchgarvie is a peak of basaltic trap-rock or whinstone, and lies to the east side of the centre line of the bridge. It rises abruptly from the bed of the Firth except at its western extremity, where it widens into a broad toe with a tolerably regular slope to S.W. of about 1 in 7. On the south side of Inchgarvie lies the South Channel, which is of about the same depth and width as the North Channel. Its southern edge, however, lies still about 30 ft. under water, and from it to the South or Queensferry shore there is a distance of 2000 ft., one-fourth of which becomes uncovered at low water.

In the South Channel the whinstone rock disappears about the centre, being from that point forward overlaid by a bed of very hard boulder clay of great thickness, this being in turn overlaid by about 40 ft. of a softer clay, gravel, silt, and soft mud. The ground rises from the edge of the deep water channel towards the shore with a gentle slope, the clay disappearing about half-way up, and giving place to ledges of freestone rock. It will thus be seen that the natural configuration of the ground on the centre line of the bridge, offers points for three main supports, of which the two outer ones are about equidistant from the central one, thus indicating two large spans of equal length, while the remaining spaces to be traversed on both shores, offer every facility for the construction of satisfactory foundations. As a matter of fact there has been no single instance of the ground on which the foundations were placed being uncertain or in any way doubtful, and no anxiety need be felt in regard to this part of the Forth Bridge.

Indications of the nature of the ground on the centre line of bridge are given in Fig. 2 on Plate III. A general view across the river is shown in Plate V., from a photograph taken on September 11, 1883. The latter view shows the Hawes Inn and garden in immediate foreground, also the Hawes Pier, the Queensferry jetty, with the half tide cofferdam of No. 6 pier, and the commencement of the large cofferdam for the South cantilever end pier. It also shows the commencement of staging on Inchgarvie, and the same on Fife, with the new coastguard houses on the first elevation to the right.

The country immediately surrounding the site upon which the bridge now stands is strikingly beautiful. Whatever opinion may be held in regard to the lines of the bridge itself, it must be conceded that this bridge or any other bridge must be a discordant feature in a pastoral landscape. Standing on Mons Hill in Dalmeny Park, and looking down over its thickly wooded slopes into the broad expanse of the Forth, with the island of Inchgarvie and its old castle breasting the swift current and cutting it into two arms, which below it, unite again in a whirlpool glittering in all the colours of the rainbow, the whole backed by the Fifeshire Hills, the Ochills, and the great peaks in Dumbarton, Stirling, and Perthshire, is a view hard to be excelled in any part of the world. Hardly less fine and perhaps more grand still is the view down the estuary into the limitless ocean, from the grounds round Hopetoun House.

In the last case the horizon falls in with the line of the rails of the internal viaduct, and thus shuts out all view most completely, while the lines of the bridge itself in geometrical repetition—with severe regularity—of triangles and squares, cannot be made to harmonise in the least degree with the soft and undulating lines of the adjoining landscape. Thus the best view of the landscape is from the bridge, because the disturbing element is left out, while by far the best view of the bridge is obtained from the river, whether above or below, at a distance of a mile or so, the structure rearing itself to a great height, and being backed only by the sky. Thus viewed, its simple lines, its well-proportioned parts, its impressive air of strength and solidity and yet of lightness and grace, never fail to strike the mind of the beholder. Four-square to the wind and immovable it stands!

The view from the summit of the central tower on a clear day is magnificent. The broad river itself, with craft of all sorts and sizes, in steam or under sail, running before the wind, cutting across the current on the tack, or lazily drifting with the tide, is always a most impressive spectacle upon which one can gaze for hours with an admiring and untiring eye. And such it is, whether viewed in the glory of sunrise or sunset, in broad daylight with the cloud shadows flying over the surface, and a thousand ripples reflecting the sun's rays in every conceivable shade of colour, or in the soft haze of a moonlight night. The sunsets in summer are always magnificent, whether due to Krakatoan volcanic dust or to the vapours of the distant Atlantic, but there have also been many sunrises in early autumn when a hungry man could forget the hour of breakfast, and one could not find the heart to chide the worker who would lay down his tools to gaze into the bewildering masses of colour surrounding the rising light of day. An unbounded view more than 50 miles up and down river! Far away to east the May Island, often so clearly defined, though 35 miles distant, that the sunlit cliffs are clearly visible, the Bass Rock and North Berwick Law, and the coast line of Haddingtonshire with the Lammermuir range fading into the sky, nearer Inchkeith with the white walls of the coastguard station and the lighthouse, Inchmickry and Cramond Island, the long jetties of Leith Harbour and the shorter of Granton and Newhaven, the roads full of shipping, the masses of houses in the marine suburbs of Edinburgh, Arthur's Seat and Corstophine Tower just peeping over Mons Hill and the woods of Dalmeny Park. To the south, the fertile districts of the Lothians gradually rising to the imposing range of the Pentland Hills, and to south-west Dundas Hill and Castle, Hopetoun House, and the old palace and church of Linlithgow, the harbours of Bo'ness and Grangemouth and the Campsie Hills closing in the upper Firth, still many miles wide with beautifully wooded shores, and many towns and villages upon its banks. Nearly 60 miles to the west, as the crow flies, stands the massive cone of Ben Lomond, and behind it a formidable array of hills and mountains, clothed in the summer-time in the tenderest shades of purple and blue, in the winter showing forth boldly in a coat of purest snow. In the north-west appear the Ochills, in the north and north-east the Fife Lomonds and the beautiful coast of Fife running down into the horizon, where, glancing over the old priory on Inchcolm, the eye catches the May Island again.

At night too a sight is presented not easily forgotten; the flashing lights of the May and of Inchkeith, and many others stationary, such as the harbour lights of Granton, Leith, Newhaven, and Burntisland combine to form a beautiful picture. At times of continued east wind, when large and small craft run for shelter in the Firth, it is not unusual to see from 150 to 200 vessels anchored in the roads, and the long straggling lines of their masthead lights give the appearance of a busy town of many streets having suddenly risen from the waters.

On Jubilee night (21st June, 1887), although the atmosphere was somewhat thick, 68 bonfires could be counted at one time on the surrounding hills and isolated points, while the great masses of the central towers of the bridge lighted up by hundreds of electric arc lights—Lucigen and other lamps—at various heights where work was carried on, formed, with their long-drawn reflections in the waters of the Firth, three pillars of fire, and afforded a truly wonderful and unique spectacle.

Tides, Wind, Wind Pressures, and Gauges. Climate Generally.

The tidal rise at Queensferry, that is, the difference between high water and low water during ordinary spring tides, is 18 ft., rising occasionally to 21 ft. and even 22 ft. Owing to the contraction in the river, already spoken of, the velocity of the tide flow is considerable, more especially so in the North Channel. The strong currents running to each side of Inchgarvie have given a good deal of trouble, both during the erection of the extensive iron girder staging between the four main supports, and between them and the rock, and during the founding of the piers. Still more was this difficulty felt during the erection of the Inchgarvie north cantilever, when it was necessary to lift all material out of steam barges up to the structure direct, and when the combined influences of tide flow, set of current and wind, made it next to impossible to keep the barges in place for a sufficient time to allow the lifting tackle to be attached even with a most skilful and experienced skipper at the helm.

The only other drawback due to tidal action, was due also to the want of proper pier accommodation upon all three points. Until the timber stages and jetties were built, none of the landing places could be approached at low water except by small boats, and there was consequently a grievous waste of time from that cause in the early days.

The prevailing winds are from the S.W. and the highest pressures recorded upon the wind gauges have invariably proceeded from that quarter; next in point of frequency occurs an E.N.E. wind, which brings up heavy seas from the German Ocean, and which is as unpleasant to the senses and as trying to the temper as the proverbial east wind in London. From the N.W. come occasional blasts which have the effect of completely clearing the atmosphere, so that the most distant mountains show with considerable distinctness their every form and detail. S.E. winds bring rain and dirty weather invariably, and are fortunately not of frequent occurrence. It is a curious fact that while in spring and summer the east wind brings with it an icy chill, while the west winds are warm and genial, the latter in the winter time bring whatever frosty weather comes to pass, which is immediately broken up into thaw by a change in the wind to east.

East winds are prevalent generally in April, May, and June, but sometimes continue right through the summer, but for the remainder of the year, often for many weeks without change, the south-west wind keeps in possession.

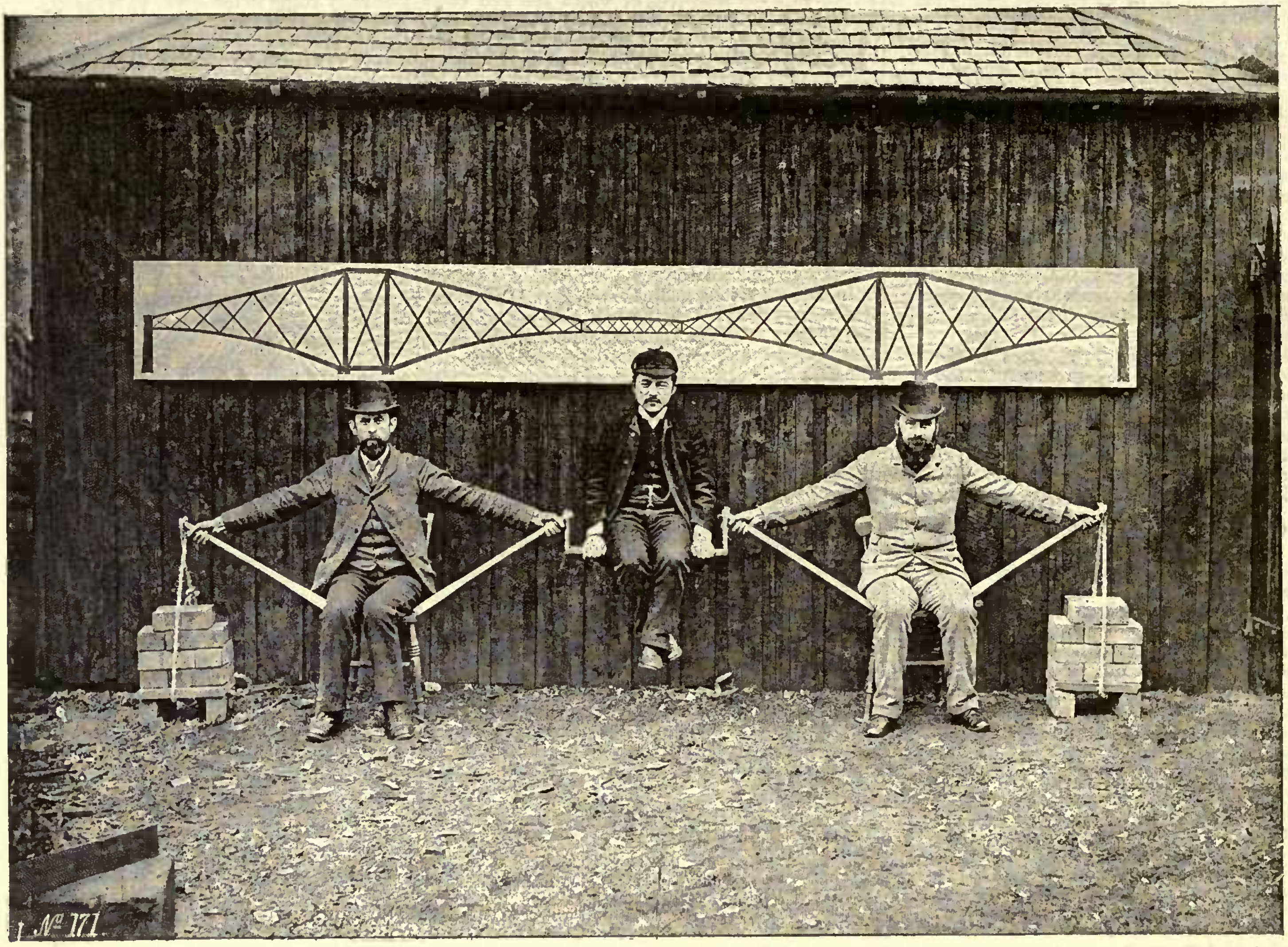


Fig. 5a. Living model illustrating principle of the Forth Bridge.

On three or four days during the year gales blow with such violence as to stop even large paddle boats from attempting the passage. On many other days the smaller barges and launches have to keep within shelter. During such times all outside work was necessarily stopped owing to the impossibility of handling material by the derrick cranes, or of getting about on the exposed stagings. From twenty-two to twenty-three full working days in the month must be considered very satisfactory in this climate; on many days only an hour or two need have been lost but for heavy rains in the early hours, which drenched the men and sent them to their homes. When such happened no power of persuasion was great enough to bring them back to work again, even if the weather turned fine and continued so for the rest of the day—a curious fact not easy of explanation.

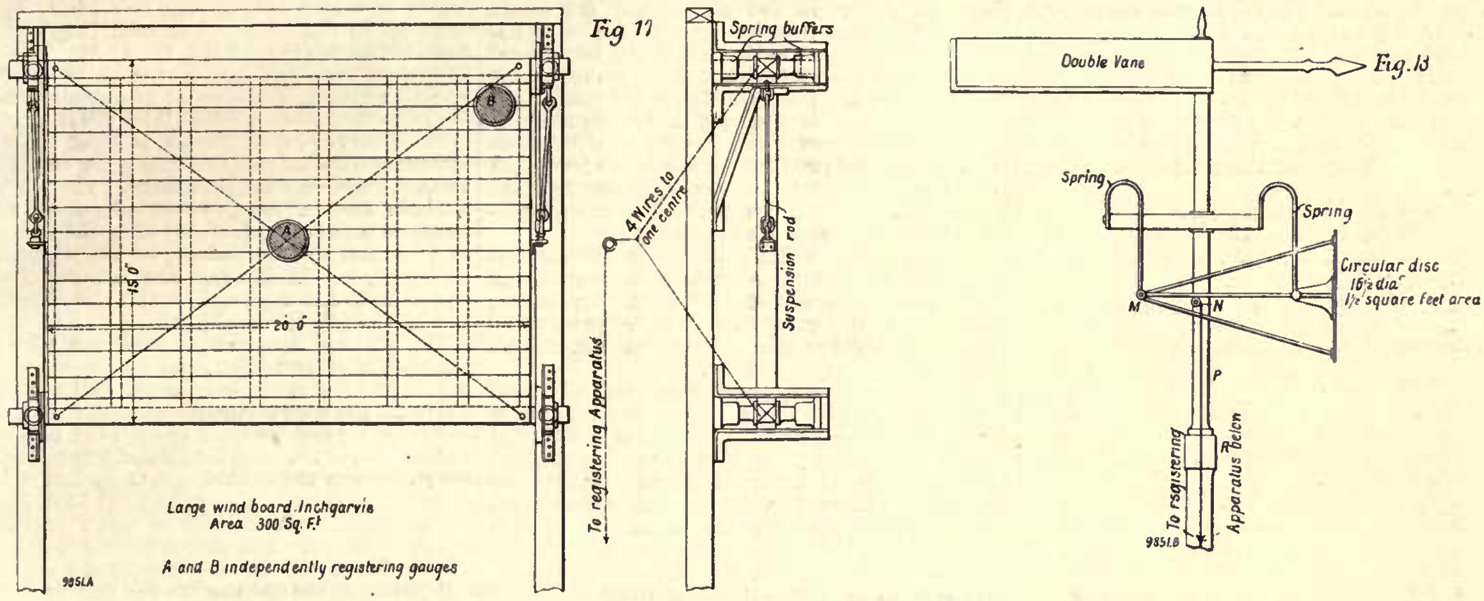
Of snow there was but little during the seven winters, and but few days were lost through its covering the ground, but the frost caused much stoppage in a work where hydraulic appliances were so largely used, and where, owing to the enormous extent to which pipe leads had to be carried, it was impossible to effectively protect them all. It was thus the practice to break a number of joints and allow all pipes to drain dry after work stopped at night. Some of these joints were on deck, others on the very top of the structure, and a fire which occurred one night, February 13, 1889, on Inchgarvie spread to an alarming extent, and might have had most serious consequences to the lower portions of the steelwork as well as to the granite piers before the joints could be closed and the pumps made effective. The danger was all the greater that a furious gale was blowing from the south-west, which made it a matter of some danger to get to the island at all, or when there to ascend to the top of the superstructure to find the broken joints.

The variations in temperature are not excessive, and may be said to range between 20 deg. Fahr. and 85 deg. Fahr. minimum and maximum in the shade respectively.

Far greater than storms to the sailing craft passing the bridge is the danger from sudden calms which frequently occur during spring tides when a strong ebb is running, and which cause them to drift about helplessly in the powerful currents. At such times the barges and launches belonging to the works were on the look-out to run to the assistance of any shipping becalmed and tow them into mid-channel. To ward off all craft from the iron staging on Inchgarvie, where they would certainly have come to grief, but where they also might have done considerable injury to the structure in the early days

Fig. 16. Map of the Firth of Forth.

of erection, three timber booms, each boom consisting of three heavy Oregon pine logs, were moored to the west of Inchgarvie. The logs were octagon section, from 2 ft. to 2 ft. 6 in. across, and about 100 ft. long, and were strongly bound together by three heavy iron belts to each boom. Mooring blocks weighing nearly 40 tons each were laid down in the bed of the Firth, some 120 yards west to the booms. On the side of the island heavy iron stakes were fixed in the rock, and to these or else to some of the iron columns, 1½ in. cable chains were attached. The other ends of these chains were shackled to the pointed ends of large floating buoys, and the same shackles received similar chains coming from the large mooring blocks. On the tops of the buoys were large rings, and to these were attached the chain bridles from the ends of the floating booms, or rather from the iron belts near the ends. Sufficient slack was allowed in all chains for rise and fall of tide. These timber booms have been the means of saving many small boats and sailing schooners from certain shipwreck.



WIND GAUGES ON INCHGARVIE.

With the calm weather in winter and early spring the sea fogs or eastern haars occur with tolerable frequency, and have caused much anxiety on account of the necessity of having to carry large numbers of workmen—many hundreds every morning and night—from either shore to their destinations. These fogs come up the Firth like a solid wall of dazzlingly white cloud, sometimes leaving the tops of the towers standing out clearly in the sunshine, at other times hanging some 50 ft. to 100 ft. up in the air, and leaving the lower portions quite clear. The effect is well shown in the illustration from a photograph given on Plate XIII.

Wind Pressure and Wind Gauges.

The wind pressure to be provided for in the calculations for bridges in exposed positions is 56 lb. per square foot, according to the Board of Trade regulations, and this twice over the whole area of the girder surface exposed, the resistance to such pressure to be by deadweight in the structure alone.

The most violent gales which have occurred during the construction of the Forth Bridge are given with the pressures recorded on the wind gauges in the annexed Table, No. I.

TABLE No. I.—Records of Wind Gauges on Inchgarvie during Violent Gales.

Year.	Month and Day.	Pressure in Pounds per Square Foot. Revolving Gauge.	Small Fixed Gauge.	Large Fixed Gauge.	In Centre of Large Gauge.	Right-hand Top of Large Gauge.	Direction of Wind.
1883	December 11	33	39	22	—	—	S.W.*
1884	January 26	65	41	35	—	—	S.W.*
1884	October 27	29	23	18	—	—	S.W.
1884	,, 28	26	29	19	—	—	S.W.
1885	March 20	30	25	17	—	—	W.
1885	December 4	25	27	19	—	—	W.
1886	March 31	26	31	19	—	—	S.W.
1887	February 4	26	41	15	—	—	S.W.
1888	January 5	27	16	7	—	—	S.E.
1888	November 17	35	41	27	—	—	W.
1889	,, 2	27	34	12	—	—	S.W.
1890	January 19	27	28	16	—	—	S.W.
1890	,, 21	26	38	15	—	—	W.
1890	,, 25	27	24	18	23½	22	S.W.byW.

* These data are unreliable, owing to faulty registration by the indicator needle, as will presently be explained They were altered after this date. The barometer fell to 27.5 in. on that occasion—over ⅜ in. within an hour.

It is worthy of observation that only one gale from easterly direction is recorded—January 5, 1888—but there have been a number of gales from that quarter registering between 15 lb. and 16 lb. and up to 20 lb. per square foot, and, of course, the same from other directions.

The pressure gauges which were put up in the summer of 1882 on the top of the old castle on Inchgarvie, and from which daily records have been taken throughout, were of very simple construction. As the object was to ascertain only the maximum pressures which the structure would eventually have to resist, the maxima only were taken. The most unfavourable direction from which the wind pressure can strike the bridge is at right angles to the longitudinal axis, or nearly due east and west, and two out of the three gauges were fixed to face these directions, while a third was so arranged as to register for any direction of wind. There was no provision made for registering intermediate pressures, nor particulars as to direction of wind or times of occurrence, except in so far as the records were taken generally at 9 a.m. every day.

The principal gauge (Fig. 17) is a large board—20 ft. long by 15 ft. high, or 300 square feet area—set vertically with its faces east and west. The weight of this board is carried by two rods suspended from a framework surrounding the board, and so arranged as to offer as little resistance as possible to the passage of the wind, in order not to create eddies near the edge of the board. In the horizontal central axis of the board there are fixed two pins, which fit into the lower eyes of the suspension-rods, the object being to balance the board as nearly as possible. Each of the four corners of the board is held between two spiral springs, all carefully and evenly adjusted so that any pressure exerted on either face will push it evenly in the opposite direction; but on such pressure being removed, the compressed springs will force the board back to its normal position. To the four corners four wires are attached, uniting in pyramidal formation in one point, whence a single wire passes over a pulley to the registering apparatus below. This in the original arrangement consisted of two levers at right angles to one another, the shorter one—about one-third of the other—being acted on by the wire from the windboard, the longer one with an index pointer registering the amount upon prepared paper slips. The indication by the pointer was thus about three times the amount of travel of the wire up and down. In order to ascertain, to some extent, how far great gusts of wind are quite local in their action, and exert great pressure only upon a very limited area, two circular spaces—one in the exact centre, and one in the right-hand top corner—about 18 in. in diameter, were cut out of the board, and circular plates inserted which could register independently the force of the wind upon them.

By the side of this large square board, at a distance of about 8 ft., another gauge—a circular plate of 1½ square feet area, facing east and west—was fixed up with separate registration. This was intended as a check upon the records given by the large board.

Another gauge of the same dimensions as the last, but with the disc attached to the short arm of a double vane, so that it should face the wind from whatever direction it might come, was set up (see Fig. 18). This also had a separate registering apparatus arranged in the same manner as the two first described.

Fig. 17 gives two views of the large wind-board with the two independent gauges at A and B. Fig. 18 shows the revolving wind gauge, consisting of a circular disc hung in four bent springs, and rods which centre in the point M. Here a horizontal crossbar connects the two opposite springs, and to this bar, immediately opposite the centre of the hollow vertical spindle P, a small chain is attached, which passes through a slot in P over the pulley N, and right down the centre to the registering apparatus below. The double vane is fixed upon P, which revolves in the socket column R. The small fixed gauge is of the same construction and area,

the only difference being that the vane is absent, and P is a fixture in R and cannot turn. The circular disc of course faces west.

It is needless to say that these gauges were not expected to give very accurate records of the wind pressures which occurred since they were put up, but they give a sufficiently approximate idea of what the structure will hereafter have to encounter in the way of wind.

Upon one occasion the small fixed board appeared to register 65 lb. to the square foot, a registration which caused no little alarm and anxiety. Mr. Baker, however, declined to accept the figures recorded, and on investigation found that, with the lever multiplication-pointer, it was not difficult to obtain high figures, owing to the lever acquiring momentum from a suddenly applied force such as a strong gust of wind would produce, thereby overshooting the mark. Thus a blow of about 20 lb. applied smartly to the gauge would register 65 lb., and would probably have registered more but that the pointer could go no further. This occurred in January, 1884, and since then the recording apparatus has been altered, the horizontal lever being done away with, and a vertical bar—suspended directly from the wire of the gauge—being substituted.

Since then the highest pressures recorded have only been 35 lb., 41 lb., and 27 lb. respectively.

A gale on March 31, 1886, gave the following results:—

Upon the small fixed gauge	31	lb. to the sq. ft.
,, revolving ,,	26	,, ,,
In the centre of the large board	28½	,, ,,
,, upper corner ,,	22	,, ,,
All over the large board	19	,, ,,

These figures seem to indicate that the higher wind pressures come more in gusts and sudden squalls than in a steady and even pressure extending over a large area.

After the central towers had been carried up to the full height, two additional revolving gauges—one at the north-east and one at the south-west corner of each tower—were put up and records taken and compared with those given by the other gauges. The records confirm most distinctly the results of the smaller gauges inserted upon the large board—for the pressures recorded vary as much as 10 lb. and 12 lb. between the different piers—sometimes the one, sometimes the other, showing the higher registration.

Experiments on Wind Stresses.

The scanty information existing on the very important subject of the action of wind pressure on the surfaces of structures, whether flat or curved, induced Mr. Baker to make a series of experiments, upon the results of which it would be possible to form some definite conclusions. These experiments are so interesting, and the appliances by which they were obtained were so ingenious, that no apology is needed for their repetition here. Realising the difficulty of working with models in actual wind, which is never, so to speak, of the same intensity or direction for two consecutive moments, and labouring under the disadvantage of not having an instrument which would reliably indicate the actual pressure at any time, Mr. Baker simply reversed the order of things by making the wind stationary and the apparatus movable. The latter then consisted of a light wooden rod, suspended in the middle, so as to balance correctly, by a string from the ceiling. At one end of the rod was attached a cardboard model of the surface the resistance of which was to be tested, be it a portion of a round tube, a flattened strut, a piece of top member, or of the internal viaduct, or even of a whole cantilever. On the opposite end of the rod was placed a sheet of cardboard facing the same way as the model, so arranged that by means of another and adjustable sheet, which could slide in and out of the first, the surface at that end could be increased or decreased at the will of the operator.

The mode of working this contrivance is for a person to pull it from its perpendicular position towards himself, and then gently release it, being careful to allow both ends to go together. If this is properly done, it is evident that the rod will in swinging retain a position parallel to its original position, supposing that the model at one end and the cardboard frame at the other end are balanced as to weight, and that the two surfaces exposed to the air pressure coming against it in swinging are exactly alike. Should one area be greater than the other, the model or the cardboard sheet, whichever it may be, will be lagging behind, and twist the string. By now increasing or diminishing the area of the cardboard sheet and repeating the experiment over and over again, a point will be reached when the whole mass will swing without twisting being produced. The area of the cardboard will then represent the exact area of the model which is affected by wind pressure.

The experiments carried on in various ways by different people and at different times are generally in agreement with each other, and not very different from those arrived at by scientists with most complicated apparatus, and by laborious and painstaking processes.

The points on which reliable information was more particularly wanted were in respect of surfaces more or less sheltered by those immediately in front of them. In the case of any box lattice girder, for instance, assuming that the wind was blowing fully square at it, it might also be assumed that the side nearest the wind would cover the side of the girder lying behind; but if the wind blows at an angle to the girder, it is certain that the second surface receives its proportion of full pressure of the wind; and in cases where two lattice box girders are close together—as, for instance, in the top member—all four surfaces will receive a proportionate amount of wind pressure.

It may easily be understood that the distance from each other of these surfaces has a great deal to do with the amount of wind stress they receive, and it was with a view of obtaining some useful data with regard to this question that Mr. Baker's experiments were carried out.

Information exists about flat surfaces and curved surfaces, and also about cubes—that is, two or more sides of any rectangular box or girder upon which the wind acts in a more or less diagonal direction. In all these Mr. Baker's experiments agreed with those of other observers, and obtained with different apparatus; but in the case of sheltered surfaces the results were somewhat different. On the whole, however, Mr. Baker satisfied himself that in no case was the area affected by the wind in any girder which had two or more surfaces exposed more than 1.8 times the area of the surface directly fronting the wind. As the calculations have been made for twice this area, the stresses which the structure will receive from this cause will be in all cases less than those provided for.

Mr. Baker also tested models of girders built of metal, both in air and in water, and although some slight differences with the former result were found, yet on the whole they fully confirmed the general conclusions arrived at.

The observations now made on the completed structure will no doubt help to throw further light on this subject of great importance to engineers, since in large structures the wind stresses are of considerably greater moment than the train loads, and should therefore, for economical considerations, be reduced to the narrowest limits compatible with absolute safety.

General Description of the Structure.

(See Plate III., Figs. 1 to 29).

From the general view of the bridge in profile it will be seen that it consists of two approach viaducts and of the cantilever bridge proper. The viaducts only differ in extent; the height above water and the lengths of the spans being the same. It will also be seen that a similar viaduct which forms the railroad or permanent way is carried through the cantilevers and central towers at one uniform level.

Commencing at the south end there are four granite masonry arches which terminate in the abutment for the South Approach Viaduct. Here the girder-spans commence—10 in number—the end of the last being supported in the south cantilever end pier. On the north shore there are three similar masonry arches, terminating in an abutment, and five girder-spans to the north cantilever end pier.

The bridge proper consists of three double cantilevers and two central connecting girders. Each double cantilever consists of a central tower supported on four circular masonry piers—a cantilever projecting from each side of it. The two outside piers—the Fife and Queensferry—have, in addition to the four supports of their central towers, a further support, inasmuch as their outer cantilevers rest in the cantilever end piers. No such additional support was available in the case of the Inchgarvie pier, and the length of the base has here been nearly doubled. The reasons for this are given further on.

The length of the cantilever bridge is 5,330 ft., consisting of the central tower on Inchgarvie, 260 ft.; the Fife and Queensferry central towers, 145 ft. each; the two central connecting girders, 350 ft. each; and six cantilevers of 680 ft. each. The cantilever end piers are apart 5,349 ft. 6 in. from centre to centre. The South Approach Viaduct is 1,978 ft. long from centre of cantilever end pier to end of arches, consisting of ten spans of 168 feet each; four arches of 66 ft. each centre to centre, and 34 ft. made up by abutments. The North Approach Viaduct is 968 ft. 3½ in. long to end of arches, consisting of five spans of 168 ft. long; three arches of 37 ft., 31 ft., and 46 ft. centre to centre respectively, and 14 ft. 3½ in. made up by abutments. The total length of the structure is therefore 8,295 ft. 9½ in. The two main spans are 1,710 ft. from centre to centre of vertical columns, made up of two cantilevers of 680 ft. each, and one central girder 350 ft.

The waterway to be crossed is about 5,700 ft., extending from the south circular piers on Fife to Viaduct Pier No. 3 at Queensferry. The rail level has been fixed at 157 ft. above high water, which leaves for a total length of 500 ft. in the centre of each channel a clear headway of 151 ft., no train load being on the bridge. The ordinary load of two trains is not expected to diminish this headway by more than about 3½ in.

The Fife and Queensferry Piers are alike and identical in every respect, and only reversed with regard to their outer cantilevers. All six cantilevers are the same in length—namely, 680 ft. from centre of vertical columns to centre of endpost—and are also of the same height and width, namely, 330 ft. high at the central towers, by 120 ft. wide at bottom, and 33 ft. wide at top, and 34 ft. high at the endposts, with a width of 32 ft. at bottom and 22 ft. at top. The only difference in the cantilevers lies in the arrangements of the endposts, and further in the fact that the two outside or fixed cantilevers of Fife and Queensferry are somewhat heavier in construction than the others. Each cantilever consists of a bottom member, or compression member, and a top member, or tension member—these being braced together vertically by six pairs of cross-bracings on each side, and being closed at one end by the vertical columns, at the other end by endposts. The space occupied by each pair of side-bracings is termed a bay, of which there are six in each cantilever. The bottom members are connected together by twelve sets of horizontal diagonal bracings intersecting in centre line, and further by the trestles and cross-girders, which carry the internal viaduct. The side bracings connecting top and bottom members consist each of a strut or compression member and a tie or tension member intersecting one another, and being connected at the intersections by strong gusset-plates and other stiffening. Each pair of opposite struts is connected by diagonal wind-bracings both above and below the internal viaduct, and by a cross-girder at top between the top members. From the intersection of struts and ties in the sides of the cantilevers, lattice girders, called vertical ties, are carried downwards and attached to the bottom members, relieving the latter of deflection between the junctions. Cross-sections of the cantilevers at each pair of struts and each pair of vertical ties are given in Plate III., Figs. 11 to 29.

Each central tower is formed of four columns, each column resting on a circular granite pier. Transversely all these piers are 120 ft. from centre to centre, or 60 ft. on each side of the centre line of the bridge. Longitudinally these piers are 155 ft. apart from centre to centre in the Fife and Queensferry Piers, and 270 ft. in the Inchgarvie Pier. It follows that the central tower on Inchgarvie is much heavier in construction and different in several features from the other two.

All the circular granite piers are carried to a height of 18 ft. above high water, and the height between the centres of bottom members and top members is 330 ft., measured vertically, which gives an extreme height of the central towers above high water of 361 ft.

The vertical columns—so called for distinction—are vertical only in one sense; that is, when looking broadside on. In the other sense, looking along the centre line of the bridge, they have an inclination of about 1 in 7½, being apart, centre to

centre, 120 ft. at bottom and 33 ft. at top. This batter of the vertical columns is maintained throughout the cantilever bridge. It had been intended to so arrange the sides of the cantilevers that the batter of 1 in $7\frac{1}{2}$ in the central towers should gradually decrease until a vertical position was attained in the endposts and the central girders; but this plan would have led to considerable complications in the junctions both in top and bottom members, and in the intersection of struts and ties, and would have produced a twisted top member.

There can be no doubt that the arrangement of a uniform batter throughout the structure adds materially to its appearance, by giving it harmonious and simple lines, and heightens the impression of stability and resistance to lateral wind pressure.

The investigations and experiments made by Mr. Baker, and extending over several years, have led to the decision that all members under compressive stress should be of tubular form—circular by preference where admissible—this form being the strongest, weight for weight. This rule is, for structural reasons, only departed from in the struts of Bay 6 of the cantilevers and in the struts and top member of the central girders. All members under tensile stress are open lattice girders.

Thus the bottom members—the vertical columns and the struts in cantilevers are always under compression and are tubular in form, while the top members, the inclined ties in cantilevers and vertical ties are invariably in tension, and are of open lattice-girder form. The diagonal struts in the central towers again, although always in compression from dead load or wind pressure, receive an alternate tensile or compressive stress, and *vice versâ*, according to the direction from which the live load or train load enters on the pier. In a similar way the diagonal wind bracings between bottom members, the vertical columns and inclined struts in cantilevers, are exposed to varying stresses according to the direction of the wind, and they are likewise affected to some degree by the position of the sun.

In order to preserve balance so far as dead load is concerned, it became necessary to load the ends of the outer or fixed cantilevers to the extent of half the weight of a central girder. To this end the endposts of these cantilevers are formed in a large box built of plates and filled with dead weight to the required extent. Thus far then the conditions would be alike for all six cantilevers in the state of rest, and in the absence of wind pressure and train load. Any introduction of the latter would at once disturb the balance, and, therefore, additional weight was placed in the ends of the fixed cantilevers large enough to counterbalance any possible train load which is likely to pass over the opposite end and leave a couple of hundred tons to the good. Under these circumstances the ends of the free cantilevers in the Fife and Queensferry Piers cannot deflect except in so far as deflection is due to the elasticity of the steel. On the other hand the fixed end will receive a downward pressure of, in the case of the maximum, the weight of the counterpoise, plus the maximum train load, and in the case of the minimum, the weight of the counterpoise minus the maximum train load, and of course any number of loads varying between the two. It will thus be seen how changeable are the conditions of load in the cantilevers, and the stresses upon the different members.

In the central or Inchgarvie Pier the conditions are different. There the weight of half a central girder is carried at each end, and so far as dead load is concerned the balance is absolute. But every ton of train load introduced from either end will upset this balance at once, and it was therefore essential to provide for every contingency. The worst condition that can be assumed would be for two trains to meet in the central girder at one end. The tendency would then be to form a fulcrum of the two nearest circular granite piers and lift the structure off the two furthest piers. As it was not intended that the anchorage in these piers, that is the holding-down bolts, should ever be brought into play except under the most improbable conditions of hurricane pressure, it was necessary to make the base of the central towers so great that the contingency stated above could not possibly arise. It is for these reasons that the central tower of the Inchgarvie pier has so much longer a base than either the Fife or Queensferry.

The four vertical columns are combined together and are braced in various ways. Longitudinally they are connected at bottom by the horizontal portions of the bottom members, and at top by those of the top members, both of these being carried through in unbroken section. The four corners of the rectangle thus formed are connected by a pair of diagonal struts intersecting each other at the centre.

In order to facilitate the intersection these struts—and for similar reasons the struts in the cantilevers—are flattened throughout on both sides, and at the points of intersection are considerably stiffened and almost doubled in the plates. At this point a horizontal bracing girder is carried across and attached to the vertical columns on either side. In the case of the central tower on Inchgarvie, owing to the greater distance between the piers, the top and bottom members cannot be carried for the whole distance without deflection, and a vertical tie is therefore brought down from the intersection of the diagonal struts and attached to the bottom member, while a vertical supporting column is carried up from the same point to take up the deflection in the top member.

In the lateral sense at the base of the columns there are two horizontal bracing girders and one pair (in the case of Inchgarvie two pairs) of horizontal diagonal bracing girders of great strength and stiffness, thus forming with the horizontal bottom members a very rigid framework immediately over the circular masonry piers. A similar double set of cross-bracings—though of much lighter section—is placed at the level of the intersection of the diagonal struts, thus bringing these points into direct connection with the four vertical columns half way up the towers. Between the vertical columns are placed four sets of vertical cross-bracings, the lowest of which also assist in carrying the internal viaduct at these points, and horizontal bracings at top between the top members. A similar bracing is placed between top members at the top of the central supporting columns and the vertical central ties on Inchgarvie above described.

All these members combined together form a tower of immense strength and weight, well able to take up and resist the enormous stresses resulting from the combined influences of dead load, live load, and wind pressure upon the tower itself and upon the cantilevers projecting from it. All these stresses, however, must ultimately resolve themselves in those portions immediately resting on the circular masonry piers, which are called the skewbacks or main junctions. These junctions are the gathering points of five tubular and five latticed girders, and as their construction will be described in detail further on, it is only necessary to mention here that they terminate at foot in a flat plate called the upper bedplate, which is so arranged that it rests on, and, in some cases, can slide or move on another bedplate, the lower bedplate, which is fixed to the masonry pier.

The functions of these bedplates in resisting and yet partially yielding to the wind-pressure and in taking up the expansions and contractions in the central towers are of so important a nature that they have received a very large amount of care and thought on the part of the engineers. The difficulties were avoided in the original design of Messrs. Fowler and Baker, and were consequent upon the modifications introduced by the other consulting engineers.

It had been the intention originally to make the skewbacks an absolute fixture upon the piers, after having given an initial compressive stress to the horizontal tubes between the piers, also to clothe these tubes inside and outside with some non-conducting material which would practically neutralise the effects of heat or cold upon them. On reconsideration, however, it was decided to only fix one skewback out of the four comprised in each pier, and to allow the other three to yield to a limited and well-defined degree to the influences of temperature, and to the lateral deflections produced in the cantilevers by wind pressure, and to some degree also by the heat of the sun.

It suffices for the moment to say that, for various reasons, the south-east pier on Fife, the north-east pier on Inchgarvie, and the north-east pier on Queensferry, were chosen as the fixed points. The arrangements of the bedplates, and the reasons for these arrangements, will be stated further on in connection with the provisions made for expansion and contraction in the main spans, and for distortions produced by wind pressures.

It will be noticed that the bottom member in the cantilevers is not arched or curved, but polygonal in form, each portion from junction to junction being a straight line and passing into the next portion with a nick or kink. Apart from the fact that a piece of straight tube is stronger than a bent one, some consideration was given to the manufacture of the plates for these tubes. Had they been curved, nearly every plate on the circumference would have had to be shaped in a different die—a difficulty still more increased by the decreasing diameter of the tube from 12 ft. at the skewback to $6\frac{1}{2}$ ft. at the end of the fourth bay, after which the member becomes gradually rectangular in form.

The top member, being always in tension, is straight from the top of the vertical columns to the top of the endpost which closes the cantilever. It is carried uninterruptedly through all the junctions with struts and ties, though its cross section decreases gradually towards the point of the cantilever.

The central connecting girder consists of a top compression member, polygonal in form, and a straight bottom or tension member, with eight sets of vertical cross-bracings to each side, consisting of struts and ties, the struts being, as in the cantilevers, provided with diagonal wind-bracings. The top members are also connected by sixteen sets of diagonal horizontal wind-bracings. From the points of intersection of struts and ties a vertical lattice tie is brought down to carry the bottom member midway between junctions. The bottom members are connected by solid plate girders going right across—these carrying the rail troughs; and they are further stiffened by diagonal T bracings and by the solid floor of buckle plates.

The internal viaduct which carries the permanent way of a double line of rails and a footpath on each side, consists in the main of two lattice girders, set 16 ft. apart, centre to centre, and of varying depth, according to the length of span. Both top and bottom booms are trough-shaped, the top booms receiving the longitudinal sleeper and rails. A cross-bearing girder occurs about every 11 ft., and upon this are laid the two inner rail-troughs, leaving the 6-ft. way between them.

The main girders differ in their construction from those in the approach viaducts, in so far as they have vertical struts and diagonal ties. They are also continuous and without break from the end of one cantilever through the central tower to the end of the other cantilever.

A footpath about 4 ft. 6 in. wide on the outside of each outer rail-trough is carried on brackets attached to gussets both to the top and bottom booms of the main girders. The footpaths are formed by buckle plates, and buckle plates are also fixed between the rail-troughs and in the 6-ft. way, thus making up a very stiff flooring. The bottom booms of the main girders are connected by horizontal cross-bracings.

It may be as well to mention that the footpaths are to be used only by the railway officials. The trains are intended to be run over the bridge at full speed, and it would be neither convenient nor safe to admit the general public.

The girders of the internal viaduct are carried between the vertical columns (and in the case of the Inchgarvie pier between the central vertical ties) by a plate-girder reaching right across, and by vertical supports carried upwards from the intersection of the first pair of vertical wind-bracings between columns. The same mode of supporting the viaduct is adopted at the centres of the first and second bays in cantilevers, while at the ends of the first, second, and third bays, as also at the centre of the third bay, trestles, supported by the bottom members, are arranged. At the centre of the fourth bay a cross-girder carries the viaduct girders, and after this, the bottom member closely approaching the line of the viaduct, similar cross girders are used with short vertical supports. In bays five and six the girders are absent, and the rail troughs, stiffer in section, are there carried by cross-girders and by the diagonal wind-bracings alternately.

In the central connecting girders the rail troughs, as already mentioned, are carried by solid plate-girders about every 22 ft.

To each side of the internal viaduct a wind fence 4 ft. 6 in. high, and of lattice construction, is carried from end to end of the bridge, and on the approach viaducts.

The viaduct girders and rail troughs are rigidly fixed to the cantilevers, and form an essential part of the latter, adding considerably to the stiffness laterally of the bottom members. The only breaks

occur at the junctions of cantilevers with the central girders. The viaduct must therefore expand and contract and move in every way with the cantilevers, and these movements will be considered presently.

It remains to mention the various influences to which the structure or portions of it are likely to be exposed.

1. Expansion and contraction by changes of temperature, acting in the direction of the longitudinal axis of the bridge, and to some extent also transversely upon the circular masonry piers.

2. Influence of the sun's rays to one side or the other of the structure.

3. Wind pressure, acting at right angles or nearly so to the centre line of the bridge.

Provisions for the first are made in the sliding as distinguished from the fixed bedplates, in the joints between the ends of cantilevers on Inchgarvie Pier, and in the cantilever end piers at Fife and Queensferry.

Provisions for the second and third are made in the sliding bedplates of the two outer or fixed cantilevers, and in all the joints between ends of free cantilevers and central girders. All these movements are horizontal and are controlled and confined within specified limits.

The arrangements to meet these will be described in detail further on.

The vertical deflections due to dead load, live load, and wind pressure, whether acting singly or in combination, have already to some extent been described, and will be further considered later.

Expansion joints are also provided in the approach viaduct girders upon every second pier, two spans being made continuous, the intermediate fixed joints being, however, placed on sliding bedplates identical with the movable ones.

In the two large spans of the cantilever bridge, longitudinal movements are only possible at the Inchgarvie ends of the central girders, the Fife and Queensferry ends of the girders being fixed so far as this movement is concerned. These ends therefore move with, and in the same direction as, the cantilevers upon which they are resting.

It has already been stated that the south-east circular pier of Fife, the north-east on Inchgarvie, and the north-east on Queensferry, are the fixed points of the structure. The movements due to longitudinal expansion or contraction are controlled and limited by these fixed points, and extend from them as pivots to the various extremities of the cantilevers and central girders. The lengths affected are as follows. (See Fig. 19.)

1. The Fife central tower, 145 ft., plus outer or fixed cantilever, 680 ft., total, 825 ft. in length, the expansion of which must be provided for in the north cantilever end pier.

2. Fife south or free cantilever 680 ft., plus length of north central girder 350 ft., total 1030 ft., the expansion of which will go towards Inchgarvie, while the expansion of the Inchgarvie north cantilever, 680 ft., will go towards Fife. The total amount of movement to be provided for at the Inchgarvie end of the north central girder where the two movements overlap, will be that due to the expansion of 1710 ft. of girders.

3. Inchgarvie central tower, 260 ft., plus Inchgarvie south cantilever, 680 ft., total 940 ft., the expansion of which will go towards Queensferry, while the south central girder 350 ft., and the Queensferry north cantilever 680 ft., make up a total length of 1030 ft., the expansion of which will go towards Inchgarvie. The total movement at the Inchgarvie end of the south central girder where the two expansions overlap, is that due to a total length of $940+1030=1970$ ft.

4. The movement between the north piers on Queensferry and the south cantilever end pier is due to the same length as on Fife, namely 825 ft.

So far as observations up to this time have gone it would appear that the expansion or contraction amounts to about $\frac{1}{150}$th of an inch for each degree of temperature for every 100 ft. of girder length. The changes in temperature have, however, been so slight, and so near mean temperature that the figures cannot probably be accepted as quite correct.

Assuming for the moment their correctness, the movements would be, for 70 deg. of full range :

1. 3.61 in.
2. 7.6 in.
3. 8.62 in.
4. 3.61 in.

These figures only give about 70 per cent. of the estimated amounts, and the provision made at the four points mentioned for longitudinal movement is more than double that given above.

Commencement of Work.

Soon after the contract was signed in December, 1882, a start was made with the preparatory and temporary work.

Offices and stores as well as a workshop, hereafter known as No. 1 shed, had been erected by Mr. Arrol in connection with Sir Thomas Bouch's suspension bridge, and these were taken possession of and considerably added to from time to time.

To enable the contractors to make an early start with the permanent work, that is, the building of the masonry piers, it was necessary that the positions of these should be fixed without delay. A base line about 4000 ft. in length was laid down along the high ground on the south shore, starting from a point in the centre line of the bridge, passing along the North British Railway for some distance and terminating opposite the east breakwater at Port Edgar. Along the breakwater a timber gangway was erected, and near the far end of it, at a distance of about 3000 ft. from the base line, an observatory was built. Three points on the centre line of the bridge, one on the Queensferry shore, one on Inchgarvie, and one on the Fife shore were marked down, and their distances stated by the Ordnance Survey of Great Britain. Various other stations, about twenty in number, were laid down as required, and by means of these a most careful triangulation was made and the centres of the three main piers finally fixed. In order to verify, if possible, the correctness of the distances apart of the three principal stations on the centre line of the bridge, which had been obtained by calculation based upon the triangulation, a measurement of the north span of 1700 ft. from the centre of the north circular piers on Inchgarvie to the south circular piers on Fife was made in the summer of 1884.

In a straight portion of the North British Railway a distance of 1700 ft. had been carefully measured and marked and transferred to high posts at the side of the cutting. Upon these posts notched knife-edges were placed at the two extremities. A fine steel wire about $\frac{1}{50}$ in. in thickness was laid along the span and drawn over the knife-edges with a certain amount of stress put upon it, previously agreed upon. Thus drawn up the wire left a certain amount of sag in the centre, which was carefully measured by level and noted. Two narrow copper tags were then soldered on, to mark the end points. The wire was then coiled up and kept ready for use. The temperature also was noted.

On the two shores immediately under the piers which marked the stations, places had been prepared for levels, by means of which the amount of sag in the wire could be fixed. On a calm, cloudy day, with the temperature about the same, the wire was taken across the north channel and laid down upon the prepared knife-edges on the piers, and with the same amount of stress put upon it, and with the same amount of sag allowed, the two copper tags soldered on should have coincided with the notches in the knife-edges, provided the distance was correct.

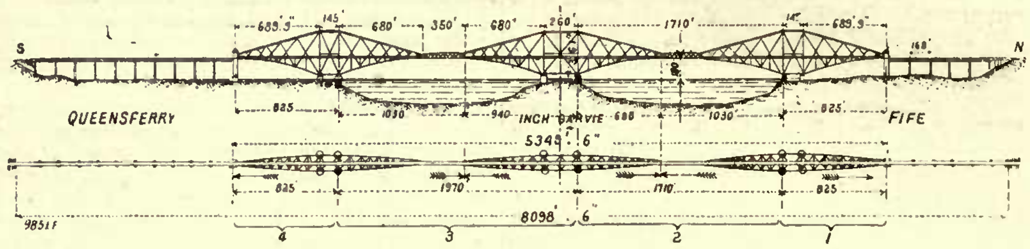


Fig. 19. Expansion diagram of Forth bridge.

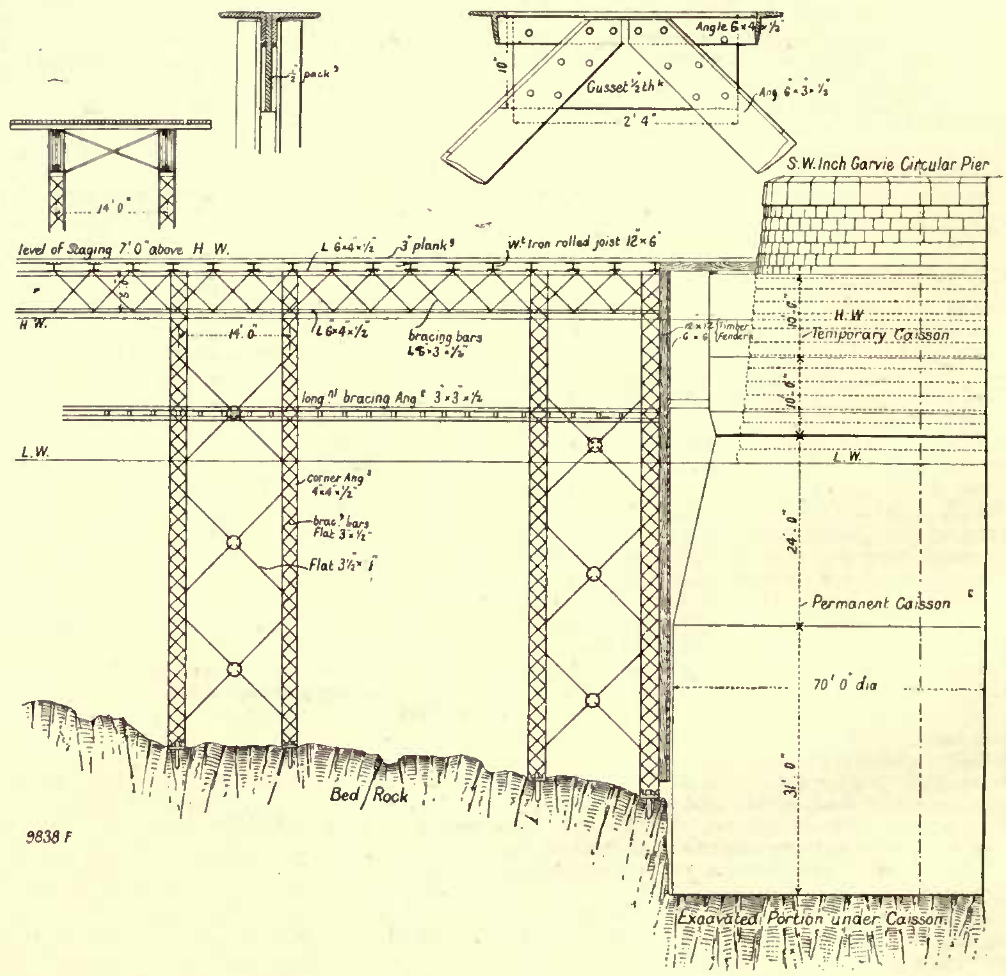


Fig. 20. Temporary staging on Inchgarvie.

It was, however, found somewhat short, and, although carefully tried several times over, the result did not vary.

Since the span has been completed the measurements made along the girders have reduced the error to about 1 in. in the north span and 6 in. in the south span, both being shorter than intended. The work of triangulation was carried out by Mr. R. E. Middleton, M.I.C.E., and a full record of his labours is given in a pamphlet published by E. and F. N. Spon, London, about two years ago.

For several reasons the positions of the four circular granite piers on Fife were first fixed, and soon the work there was in full swing. The greater portion of the old coastguard station, which was situated on the site now occupied by the north-east pier, had to be removed, and an entirely new station built on the rock further to the north, and about 40 ft. higher. The rock extending over the site of the pier had to be levelled down to about 7 ft. above high water in order to obtain ground for laying down plant, machinery, and materials. The old battery slip, the ancient landing-place for the ferry boats which slopes down from above high water to a few feet above low water, was covered over with an extensive and substantial timber staging, on which cranes were erected for unloading and moving material, and which also served for landing the workmen and for mooring barges and steamboats. (See Plates IX., XI., XII., and XIII.) Further inland, in convenient situations, wooden huts for the accommodation of the workmen and their families were erected, to which were added, later on, a canteen, stores, and dining and reading-rooms.

At South Queensferry the preparatory work was of a much more extensive character. The ground here rises rapidly from the shore at a gradient of about 1 in 2 until it reaches an elevation of about 100 ft. above the sea, and thence continues to rise with a gentle slope in a southerly direction. As a great deal of level ground was required here for workshops, drill roads, and spaces for temporarily fitting together portions of the steel-work, it became necessary to level the ground in terraces. Thus the general level of No. 1 Shed is about 12 ft. below the offices, while No. 2 Shed is about 6 ft. above these, the drill roads another 5 ft. higher, and so on. No. 1 Shed was considerably enlarged, and No. 2 Shed at once commenced, as were also the drill roads on which the tubular members had to be put together and drilled. Further to the south still some forty wooden huts were erected, together with stores for the sale of food and clothing, boots, and groceries, and a canteen with dining and reading-rooms.

To these were presently added sixteen houses substantially built in bricks for the accommodation of foremen and members of the staff, and about sixty tenements at Queensferry for leading hands and gangers.

Next to the drill roads a carpenter's and joiner's shop was erected with a saw-bench and a pattern shop, and a large drawing loft, 200 ft. long by 60 ft. wide, with blackened floor upon which full-sized drawings were prepared and full-sized templates made for drilling, planing, bending, &c., of portions of the superstructure. Telephonic communication between offices, stores, workshops, and the Queensferry, Inchgarvie, and Fife centres, was established by means of a cable laid across the Forth.

On the west side, the ground was bounded by the North British Railway to Queensferry, which here runs in a deep cutting. Two temporary bridges—girders of the ill-fated Tay Bridge—were thrown across at a distance of about 200 yards apart, and as the progress of the work required further extensions, ground was taken on the other side of the lines, until finally between 50 and 60 acres were occupied by the works on both sides of the line and right up to the Edinburgh-road. All this ground during the busy years of 1886 to 1889 was covered with girder-work under construction, and presented a striking scene both day and night.

Down by the shore to the east of the central line of the bridge a sawmill was erected, and later on a large cement store. The Queensferry jetty was commenced early in 1883, and completed in the spring of 1884, shortly before the first caisson was launched. It is a little over 2100 ft. long, by 50 ft. wide. It runs parallel with the centre line of the bridge at a distance from it of 60 ft. to about 100 ft. beyond the cantilever end pier, whence it passes by a gentle S curve right into the centre line, and terminates in a strong crosshead which embraces the four masonry supports of the Queensferry Pier. Extensions of this jetty were made during the building of the foundations and lower portions of the approach viaduct piers, but were removed again after the girders had been completed. A similar extension with landing stage for steamboats, and storage ground for building material was made round the cantilever end pier, and remained during the whole time.

The jetty is built on piles driven in the silt and soft clay down to the boulder clay. Where rock occurs, the uprights are secured on level points by being bolted to stout iron pins which are sunk in holes drilled for the purpose. There are six piles mostly 12 in. by 12 in. baulks, set in a row transversely, three on either side being bound together by half-timber cross bracings on opposite sides and the whole connected by a full timber crownhead set on top. These trestles are set about 20 ft. apart, and are held together by raking struts passing from the top of one trestle to about low-water mark of the next. Passing from trestle to trestle are 12 in. by 6 in. rolled joists about 25 ft. long, weighing 56 lb. to the lineal foot; these are set from 4 ft. to 5 ft. apart, according to position, and transversely on these the planking 3 in. or 4 in. thick, as the case may be, is laid, which forms the flooring. The level of the top of the planking is about 8 ft. above high water. The jetty was erected by means of an ordinary traveller carrying an overhanging pile-driver, which set out the piles 20 ft. in advance and drove them in. The uprights were then cut to level, the crownhead set on, the diagonal bracings and raking struts fixed, and the traveller moved forward on double longitudinals. The joists were laid down behind the traveller and the flooring made up. As this mode of working did not progress as quickly as desired, a pile-driving barge was placed near the far end and worked towards the shore. In the position of the jetty forming the T head, the piles required to be very long, as the average depth at high water was about 32 ft. and the depth of soft mud or silt, some 24 ft., requiring piles of from 65 ft. to 70 ft. in length, spliced in the ordinary way. Pointed pile shoes made of malleable iron were fixed to the lower ends.

The shore end of the jetty was connected with the under works by an inclined road laid on timber trestles, the gradient being about 1 in $6\frac{1}{2}$, with an iron girder bridge of about 65 ft. span across the Edinburgh-road. There was a single line of rails and a footpath to one side with a covered box running alongside for carrying the hydraulic pressure pipes, and also a supply of water down the jetty to Queensferry Pier. The incline was worked by a wire rope, $1\frac{1}{4}$ in. in diameter, drawn by a winding engine on the top. Down this incline all material was sent which arrived by North British Railway, whether fuel, oil, or other stores or plant and machinery, or, finally, steel-work which had been prepared in the shops and yards. Upon the jetty itself a number of service lines were laid down with sufficient room between, to store immense quantities of building material. Along the east side two lines were laid down which conveyed all the material coming down the incline to three or four heavy steam cranes, by which it was lowered into the the barges and conveyed to the landing stages on Inchgarvie or Fife. While the jetty was in course of construction, launching ways were laid down in a sheltered bay about a hundred yards to the east below, and in front of, the sawmill. They consisted of parallel rows of timbers, of sufficient width to take two caissons of 70 ft. diameter side by side. They were laid to the natural slope of the ground, which is here part rock, part shingle, and has an easy gradient of about 1 in 11. The launching ways will be further referred to in connection with the building of the caissons.

Machinery and plant of every kind and description commenced now to arrive on the ground. A siding had been laid down from the works to South Queensferry station, about half a mile distant, and another siding in the cutting alongside the shops. Cranes were set up in all convenient positions, and thus a large amount of material arriving by train could be unloaded close to, and distributed among the different shops. By this arrangement the various sections of raw steel—whether plates, bars, angles, tees, or others—could at once be delivered near the heating furnaces or drilling or planing machines where they required to be dealt with.

From this time forward for fully five years, the plant kept on increasing at an astounding rate, most of it being of a special character, and purposely designed for these works. The list of the plant on the works towards the end of 1888 is a voluminous document, and is represented in the accounts by a very large sum, not far short of half a million sterling

Inchgarvie.—The island of Inchgarvie, which Providence has so kindly placed in the middle of the Firth, is a peak of whinstone rock, about 850 ft. long at high, and 1500 ft. at low tide, and on an average not more than 60 ft. wide above water. The castle stands on the highest part of the rock about 40 ft. above high water, and the square keep is about 30 ft. high ; on the top of this the wind gauges are fixed. The distance from Inchgarvie to the Fife shore is about 1600 ft., while to the Queensferry shore it is rather more than double. Although owned by the Dundas family, whose seat is in Linlithgowshire, the authorities on the north shore claim it as belonging to the County of Fife.

The castle was built some time subsequent to 1490, on the 20th of March of which year, King James IV. of Scotland granted a license to John Dundas of Dundas to erect a fortress on the island of Inchgarde, since corrupted to Inchgarvie. The object was to afford protection to all shipping seeking refuge from the pirates with which the North Sea seems to have been infested in those days, and for giving such protection, Dundas was authorised to levy a toll of 6d. per ton. One of those persons without belief in the good old days has suggested that the Laird of Dundas not only kept a garrison on Inchgarvie for the protection of the shipping, but that he also provided the pirates in the North Sea for chasing them up the Firth ; though with regard to this both history and charter are silent.

The four circular piers are situated at the western extremity, wholly submerged at high water, although a broad ledge of rock is uncovered by the tide at low water. This portion of the island is called Craig Spurry, and upon its north-western point stands a brick pier, about 33 ft. square, and about 7 ft. above high water, the only piece of permanent work built in connection with Sir Thomas Bouch's gigantic suspension bridge. Upon it was erected, some three years ago, a lighthouse with a revolving light giving flashes about every five seconds, visible for many miles both up and down the Firth.

A spring of fresh water was said to have existed on the island, and some 40 yards east of the castle, a square well, partly cut out of the solid rock, partly formed by a brick wall, was found. It was pumped out and carefully examined, but no borehole or other inlet could be discovered, and it proved to be simply a storage tank in which the rainwater from the overlying portions of the rock collected.

On Inchgarvie the first work in connection with the cantilever bridge was carried out in the erection, during the summer of 1882, of the wind gauges on the top of the castle, and already described.

About the middle of April, 1883, the construction of a landing stage was commenced, of iron girders and iron columns pinned to the rock. At the same time the square keep of the castle, some outbuildings, and the whole of the battlements, were roofed in to afford space for the most necessary shops, offices, and stores, to which was added later on, a substantial cottage and a kitchen, and sleeping accommodation for ninety foreign workmen occupied in the sinking of the pneumatic caissons.

All over the west end of the island, the rock was cut down to the general stage-level of 7 ft. above high water, and as much ground was made up as could be obtained, by filling up with the débris of excavation and of removal of rock Some 100 yards of sea-wall had to be built as a protection against the heavy breakers rolling in from the east, and every square foot of space thus gained was of great value thereafter, when an immense amount of material required to be stored.

In the Act of Parliament authorising the erection of the bridge, the whole of the island had been included in the Parliamentary limits, but at first only the area within the four circular masonry piers, and a reasonable amount of ground for working purposes was acquired. It was soon found that this was quite insufficient for the requirements of the works, and notice of compulsory purchase by the Forth Bridge Company, was given to the proprietor. The matter came to arbitration and was settled in 1884. A sum of 1500*l.* had been paid to the proprietor for the right of placing four masonry supports on the island, and in terms of the arbitration a

further sum of 2800*l*. was paid. The island is now, therefore, the property of the Forth Bridge Railway Company.

It having been considered advisable to cover the whole area between the piers with staging, a commencement was made without delay. Owing to the nature of the bottom, which was all solid rock, it was found more expedient and safer in view of the exposed position, to make this staging of iron, and not of timber. The area of this staging ultimately amounted to more than 10,000 square yards, and the weight of iron used in its construction was between 1100 and 1200 tons. In view of this large expenditure for temporary purposes, it was deemed right to proceed on some system in the laying out the main line of girders. As the horizontal tubes, the horizontal girders between skewbacks, and the double cross of diagonal horizontal wind-bracing, required to be carried by the staging before they could be connected with the skewbacks and rivetted up, the main lines of the iron girders of the staging followed the centre lines of these members, the remaining spaces being filled in sufficiently strong to carry any weight which was likely to be put upon them during the erection of the superstructure. As this staging stood well the very severe tests to which it was subjected from various causes, and only yielded to a slight extent in places where it had been absurdly overloaded, it may not be amiss to give a few particulars as to its construction, shown in Fig. 20.

The upright columns or supports consisted of four angle-bars 4 in. by 4 in. by ½ in., braced together on all four sides by double crossbars of flat section, 3 in. by ½ in., the column being 2 ft. square. A cast-iron shoe, to which the four corner angles were bolted, formed the foot of the column, and it had a large boss in the centre with a 4 in. round hole through which a pin was passed going into the rock to a depth of about 3 ft.

The longitudinal main girders were 5 ft. in depth, and consisted of four angles 6 in. by 4 in. by ½ in., two in the bottom boom and two in the top boom, with gussets inserted between every 5 ft. apart for attaching the diagonal bracings, which were angles 6 in. by 3 in. by ½ in. placed alternately on one side or the other. The girders were carried by, and bolted to, cross-angles attached to the supporting columns. The girders carried safely a distributed load of about 6 cwt. to 7 cwt. per square foot up to 30 ft. clear span between supports. The columns were arranged in clusters of four, forming a square, the sides of which were 14 ft. taken at the centres of columns, and such clusters were placed immediately under the points of intersection in the girders of the structure overhead, or in fact in any place where much weight had to be carried. The four columns so placed were braced to each other by crosses of flat bars of heavy section 3½ in. wide by 1 in. thick, the centre of the cross being formed by a heavy ring, the flat bars terminating at that point in 1½ in. round with a thread cut upon them which passed into the ring. By a nut on either side of the ring the flat bar—the other end of which was bolted across the column—could be tightened or slackened as desired. Two or three sets of these bracings, according to the length of column, were bolted to each of the four sides of the cluster, the lower ones reaching in most cases to within a foot or two of the bottom of the column having to be put on by divers. Generally speaking these clusters were placed about every 45 ft., centre to centre, and for intermediate supports, where necessary, single columns under each girder were considered sufficient, and these would receive transversely a pair of angle-iron cross-bracings between high-water and low-water mark.

The longitudinal girders run through the uprights, spaced 14 ft. apart, and they were braced laterally about every 25 ft. by a pair of cross-angle bracings carried from top boom on one side to bottom boom on the other side and *vice versâ*.

All the girders were made in regular lengths of bars, breaking joint at 5 ft.; they were marked by template and punched, and all parts except those for closing lengths were interchangeable. All holes were punched for ⅞-in. bolts. The girders weighed just 1¼ cwt. per foot lineal, including all bracings, the columns about 64 lb. per foot lineal, including bolts.

The whole staging was erected by overhang with derrick cranes in the following way: Starting from a cluster, the next columns forward would be lowered till they nearly touched the ground, the diver would then descend and examine the bottom, selecting a nearly level bit, or otherwise dressing the rock roughly. A few bags of concrete were then lowered to him, with which he made the bed into which the column was lowered. It was then strutted by one or two light battens to the already fixed work, a 4-in. jumper lowered in the centre of the column, and a hole jumped by means of a spring pole some 25 ft. long. The jumper was lowered through a tube 4½ in. in diameter, which fitted into a socket left in the cast-iron shoe at the bottom, and acted as guide. The hole was jumped about 3 ft. to 3 ft. 6 in. deep; the jumper was then withdrawn, and a wrought-iron pin, 4 in. in diameter and 5 ft. long was dropped down the tube. The latter was then lifted up, and the diver descended to ascertain whether the pin had well entered into the rock. When the columns were fast, a length of girder was laid upon them on each side, and the crane advanced another section.

Across the longitudinal girders, 12-in. rolled joists weighing 56 lb. to the lineal foot were laid, being 21 ft. to 25 ft. in length, and therefore overhanging the girders from 3 ft. to 5 ft. The joists were bolted to the girders by hook bolts and ordinary draw-washers, and were spaced 5 ft. apart. The decking consisted of 3 in. by 9 in. planking, bolted to the top flanges of the rolled joists by bolts and draw-washers from underneath.

The staging, as first projected, was commenced in the autumn of 1883 and finished before the end of 1884, but additions became necessary from time to time to accommodate the immense quantities of material, and at times the 10,000 square yards of staging were found quite inadequate to meet the demands upon it.

All portions of the staging which had to be used as landing places for materials—and of such there were a good many—had the iron columns strengthened by bolting on heavy timbers, with half-timber fendering upon that for wear and tear. Horizontal timber struts were also set up against the backs of those columns to guard them against bending in by the action of the boats and barges upon them in rough weather.

By the time the staging was up round the north piers on Inchgarvie—these were already well forward—arrangements had to be made for the reception of the two heavy caissons for the south piers. Facing the south, therefore, two semi-circular openings were left about 73 ft. in diameter, an extra number of columns were placed in the half-circle and well braced with the others next behind, and the whole row of columns between the north and south piers, on either side, were joined together at about low-water mark by a continuous line of double angles to take the thrust from and give resistance to any possible bumping of the heavy caissons during the time they required to remain afloat.

Meanwhile plant and machinery were sent here as to the other centres, a number of offices, large workshops, stores and shelters for the men were built; also engine-houses for pumping engines, air compressors, hydraulic accumulators, electric light machinery, and much more.

Transport and Distribution of Material.

The supply, the transport, and the distribution of the materials necessary for the building of foundations and piers containing some 140,000 yards of masonry and also of some 55,000 tons of steel, and a more than equal amount of temporary appliances, was no mean task, and required the exercise of much energy and skill as well as tact and patience, for the work was equally pressing on all points, and no one liked to be left behind in that great race for supremacy.

Of the building materials, granite, Arbroath rubble, and sand were brought by water, and could, therefore, be unloaded at the various centres where required; so also could rafts of timber in baulks and planks or battens in barges, and in some instances cargoes of coal or coke, but all the other material had to come down the incline, and for these the jetty at Queensferry was the main centre of collecting and storing, as well as of distributing to the other jetties.

The steel for erection, after it had passed through the shops and had received a coating of boiled oil, and its distinguishing markings both in typing and stencilling, was passed down the incline on trollies and charged into steam barges for general distribution.

For the service of carrying materials were provided, four steam launches for the light work, and eight large steam barges, with a number of ordinary barges or lighters, which were towed by one of the launches or barges.

For the general service of conveying the workmen from or to, or between, the different main centres, a paddle steamer was hired for some time, which was afterwards replaced by one specially built for these works, and capable of carrying 450 men at a time. The steam barges, which were decked over, and the steam launches, were also used for the same purpose, as well as for the service of the engineers and other officials belonging to the staff. A large number of ordinary rowing boats were also kept in use, one of them, manned by two expert watermen, being attached to each cantilever for the purpose of saving life, should any man be unfortunate enough to fall from the erection. As a matter of fact these boats saved at least eight lives, and they saved fully 8000 caps and other garments which the wind had blown off the bridge.

Soon after the works had got into full swing it was seen that the accommodation at South Queensferry and North Queensferry and the adjoining villages, was totally inadequate for the number of workmen employed, and arrangements were made with the North British Railway Company to run trains between the works on the south side and Edinburgh, and between the north side and Inverkeithing and Dunfermline. These were all special workmen's trains and were run at merely nominal fares, the price for an Edinburgh weekly ticket being 2s., or 2d. for a run of over 13 miles. The Dunfermline tickets were about half that amount.

Two trains were run in the morning, closely following one another, and two trains at night, each train bringing a number of men going on their shift, and taking back those who had worked their shift. Some time later the train service was extended as far as Leith. It is worthy of remark that the men living at Leith, and there were several hundreds, had to leave their homes at 4 A.M., in order to be at their work at 6, and they would not on their return in the evening, reach home again before 7 o'clock, yet they preferred this to the other alternative of living in the overcrowded rookeries of the neighbourhood.

In the summer time a steamboat service was also arranged between the South Queensferry Jetty and Leith, *viâ* the Firth of Forth, calling both ways on Inchgarvie, and so long as the weather was favourable, this was a most enjoyable, and certainly healthy trip for the tired workmen.

On wet and stormy days, when the men had to leave work owing to the weather, these trains were often telegraphed for, to enable them to return to their homes, instead of keeping them till nightfall and leaving them to the tender mercies of the public-houses, of which there were in this place, as in many others, far too many.

As it was not possible to so arrange that the workmen living on the south side or north side of the Firth respectively, should be working on the same side, and as the Inchgarvie men also belonged to both sides, it required quite a fleet of steamboats and barges to convey the men to the points whence their trains started, the more so as this had to be done within a very short time after work had ceased. In bad weather, or during fogs, and on dark mornings and nights, the transport of many hundreds of men—some nine hundred working on Inchgarvie alone at one time—was a subject of unceasing care and anxiety to those in charge, for in addition to the dangers provided by the elements, there was always a number of unruly and reckless men whose conduct brought mishap and injury on others as often as on themselves.

Lighting.

The efficient lighting of so large a working area, changing every day almost, having not only to be carried forward with the work, but also upward and in all directions, was a task of considerable magnitude, and of the greatest influence upon the rate of progress. It is not so much the lighting of the actual spot where work is proceeding, but that of the approaches to these points, and of the accessory places, such as stores, engine-houses, workshops, jetties, and landing-places, which runs away with so large a proportion of the total illuminating power.

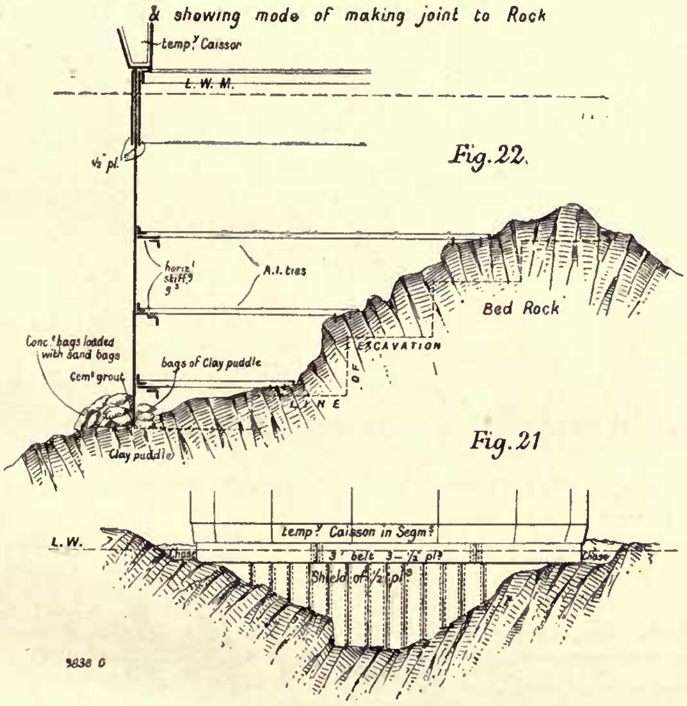
As regards the nature of the lights it was to be expected that a keen rivalry would spring up between the various systems of lighting. South Queensferry has only a small supply of gas, and that at the ruinous rate of 8s. 4d. per 1000 cubic feet; this mode of lighting was therefore out of the race. Electricity was at once resolved upon—arc lamps for the shops, and outdoor work, and incan-

descent lamps for offices, stores, fitting-shops, and such like. The latter were also used in the caissons and by divers under water, and proved of immense value in such work. The incandescent lamps were generally of 15 candle-power, but within the last few years, lamps with power up to 500 candles were used for particular purposes.

The arc lights were of 1500 to 2000 candle-power, and though every care was used to obtain the best carbons in the market and to keep the machinery going with the utmost regularity, these lights were always unsatisfactory owing to the changes in the colour of the arc and the illuminating power, the glare and flicker and the black and impenetrable shadows thrown by their own framework or by any intervening object. Generally they were arranged in circuit of six or more, and sometimes as many as twenty-one, and the sudden extinction of so many lights caused by the comparatively trivial fact of a belt slipping or a journal heating, was a source of inconvenience and much danger to the men working out on the erection, for while standing one moment in the dazzling glare of these lights they were sometimes suddenly called upon to use their eyes in absolute darkness or sit still.

Where the electric light came in as a great and lasting boon was in the lighting of the interior of the air chambers and air shafts of the large pneumatic caissons while in the process of sinking. The absence of all smoke or filth due to oil lamps of whatever description, the facility with which they could be moved, changed, put up or taken down, was of incalculable advantage in places where breathing even the purest air was a task of some discomfort and difficulty, and here, therefore, the electric light reigned supreme.

INCH-GARVIE N.W. IRON COFFER-DAM.
Section through Shield.
& showing mode of making joint to Rock



INCH-GARVIE IRON COFFER-DAM. N W. PIER.
Outside view of Shield.

BEARING OF CAISSONS ON ROCK FOUNDATIONS.

From the drawbacks mentioned above which attached to the electric arc lights, the Lucigen lamps, which were also introduced at an early period, were entirely free, though their shortcomings cannot be overlooked. There can be no doubt that for general work of erection they are the best for light, the simplest to keep in order, and the easiest to attend to. The disadvantages are that they are difficult to keep clean, as a good deal of the oil escapes unconsumed, especially in high winds, and covers girders and staging with a thick coat of slimy oil, making them slippery and unsafe. It is also difficult to get the creosote oil pure and free from sand, grit, and water, which impurities cause the small passages for the oil to choke, while the last frequently extinguishes the light. On the other hand, it is as easily shifted as an arc lamp, and is not nearly so fragile or apt to be broken.

Large incandescent lamps give a steady and most excellent light to work by, but if covered with a fine wire guard or a second globe the power of the light is seriously impaired, and if left unprotected, the smallest chip of metal, or even of wood, thrown against it, suffices to cause fracture to the globe and extinction of the light.

Except in special cases, where the work is confined to a comparatively small area, the writer has no hesitation in saying that, in the work of outside erection, under the best conditions of lighting, and with every care taken to give the men confidence in getting about their job, the amount of work done at night will not exceed 50 per cent. of that done in daylight. As a consequence of the lighting of the piers at various points and heights, and changing these almost nightly, according to circumstances, there arose a great deal of confusion to the shipping going down or coming up the Firth, and it must be conceded that on a dark night, when, for some reason or other, work was not carried on upon one of the main piers, it was difficult at the first glance to know the exact position of all the piers. On such a night, with a slight mist on, the captain of a tug-boat, coming down river with a barque in tow, mistook the lights on the Fife erection for those of Inchgarvie, and steered his ship straight for the hamlet of North Queensferry, which was hidden in the mist. He perceived his error in time to back his boat out and slip the tow-rope, but the barque continued its course and did considerable damage to itself and to the landing jetty. It is true that a glance at his compass would have shown him that a northerly course instead of an easterly could not be right; but it was in consequence of this mishap that it was decided to erect a lighthouse at the north-west corner of Inchgarvie with a revolving light giving five-second flashes. This light is at an elevation of about 30 ft. above high water, and can easily be seen for twelve miles up and down river.

As regards the cost of lighting, it was not easy under the peculiar circumstances of carrying on the work at the bridge to make comparative trials of the lights. At first the balance was much in favour of the Lucigens—the oil costing only ½d. to ⅝d. per gallon, but as the demand rose so did the cost of the oil, and ultimately it was difficult to obtain it at four times the original price.

Electric light installations, consisting of steam-engines and dynamos, as well as air compressors for the Lucigen lights, were put up on the Fife shore, at Inchgarvie, on the Queensferry Jetty, and at the workshops above, the latter being, of course, by far the most important.

During the busiest years the lighting arrangements required a separate department, and a large number of hands were kept going to attend to the lamps, the dynamo machines, the cables, and other connections. The conductors varied in size from 7 strands of No. 18 gauge wire to 19 strands of No. 16 gauge; they were supplied by Messrs. W. T. Glover and Co., of Salford.

Materials of Construction for the Masonry Piers.

It was laid down in the specification to the contract, that all piers, abutments, and arches were to be constructed of masonry consisting of a granite facing, the hearting being of concrete or of rubble masonry. The stipulations as to the quality of the stone, the amount of facing and dressing, and the quality of cement and sand, were of the usual description in contracts of this kind.

Granite.—All the granite for facing—whether rock-faced or dressed—was obtained from Aberdeen, with the exception of the large coping-stones, which weighed between 6 tons and 8½ tons each, and the necking courses immediately below the coping. These were of Cornish granite and were dressed.

The granite is grey in colour generally, and of very handsome appearance, with some slight veins of red granite running through, which, however, rather add than detract from its appearance.

The granite was brought, roughly dressed and squared, in specified courses ranging from 21 in. in thickness down to 16 in., and also specified as headers and stretchers, so as to form proper bond with the hearting of rubble masonry or concrete. Coming by water, the stone could, of course, be delivered at the respective centres at once. The granite coping-stones were 4 ft. 6 in. in depth, not less than 3 ft. in width, and set out alternately as headers and stretchers. The capping —that is, the slightly-curved crown of the piers— was set out after the coping had been built, and the correct measure of every stone was sent to the quarry near Aberdeen, each stone being numbered and marked.

Rubble Work.—For this a very hard flat-bedded and easily-split freestone—in colour from reddish ochre to purple grey—was brought from Arbroath. It was brought in large blocks up to 4 tons each, and in thickness from 3ft. downwards, but it could be split with ease into slabs not more than an inch thick.

Whinstone blocks, roughly levelled on two sides, were also used in rubble work. These were obtained either by quarrying in the open or by the excavations for the piers.

For bond courses in all the viaduct and the cantilever end piers, a hard freestone from quarries in the neighbourhood or extra large whinstone blocks were used.

All the rubble could be obtained at a cheap rate, owing to the inexpensive mode of transport in ships and the facilities of unloading close to the piers.

Concrete.—For making concrete the whinstone found both on Inchgarvie and at North Queensferry was exclusively used. A number of stone-breakers were set up in the last-named locality, where a large quantity of quarry chips were available and close at hand, and the crushers were placed in convenient positions for charging the broken stone into barges or iron skips for transport to the other centres.

The broken metal was passed over screens to obtain the required size for different purposes.

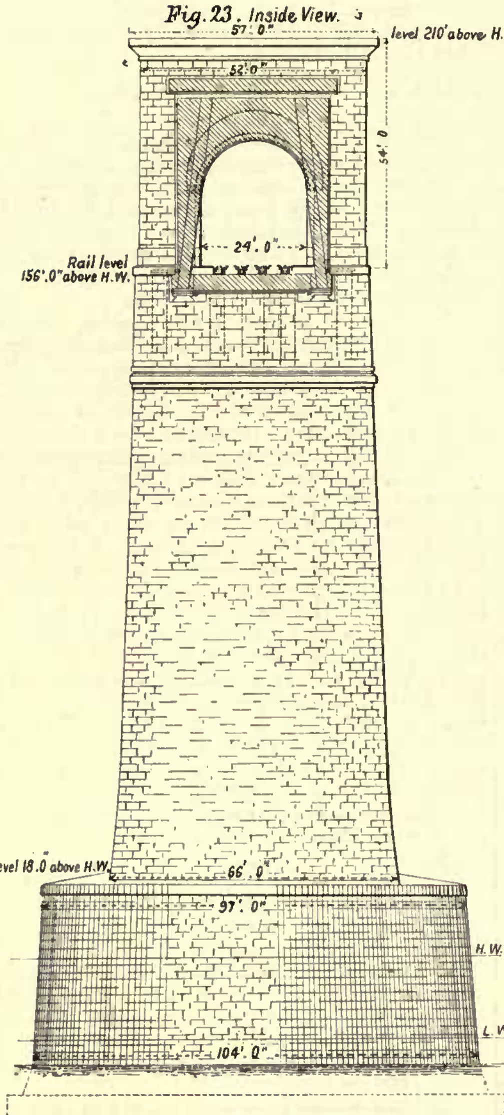
The concrete was mixed dry first, and again after the addition of water, either by hand, or, if required in very large quantities, by a very effective mixer of simple construction.

The concrete used in open foundations, in the caissons and as hearting behind the granite facing, differed somewhat in its composition according to position; but generally speaking the proportion of cement to broken stone was not less than 4½ cubic feet to the yard of stone, nor more than 6⅔ cubic feet to the yard, an equal amount of sand, or a slight excess over and above, being added. These quantities were considered as making up one yard of concrete. Such concrete had a resistance to crushing of 50 tons per square foot, and it weighed about 37 cwt. to the cubic yard.

Sand.—Some difficulty was experienced in obtaining good sharp sand. It was found in large quantities on both shores of the Firth within half a mile, but objections to its removal being raised by the proprietors of the foreshores, it became necessary to send steam barges down the Firth to Kinghorn and Pettycur, a distance of ten to eleven miles, where the tide lay some banks dry at low water. Owing to the barge having to be grounded

DETAILS OF SOUTH APPROACH PIERS.

Fig. 23. Inside View.



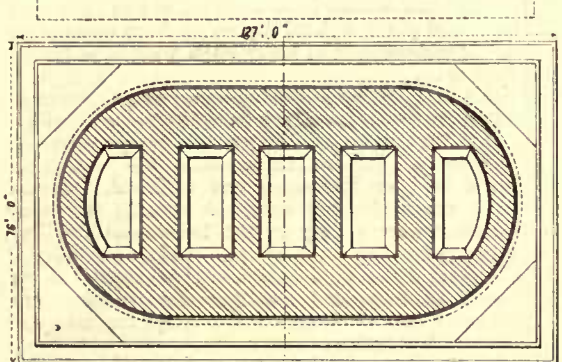


Fig. 24. Section A B & Plan

Fig. 25. Cross Section.

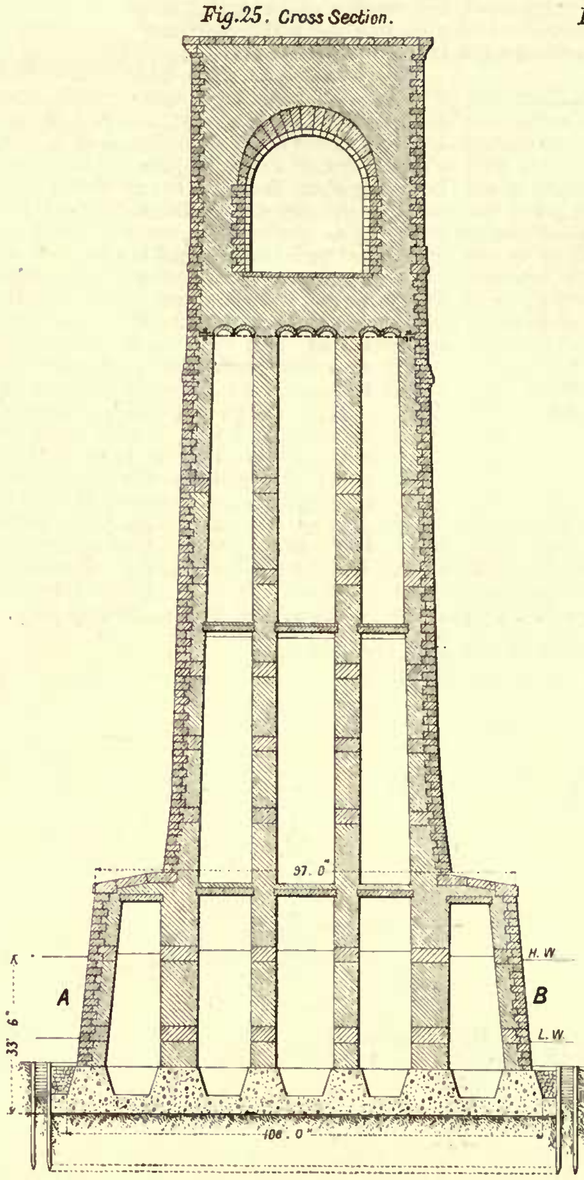


Fig. 26. Section in centre line of Bridge

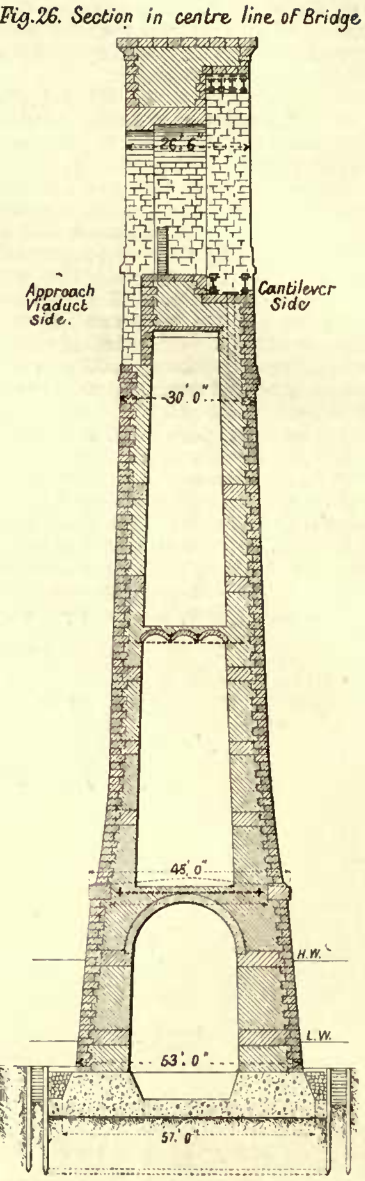


Fig. 29.

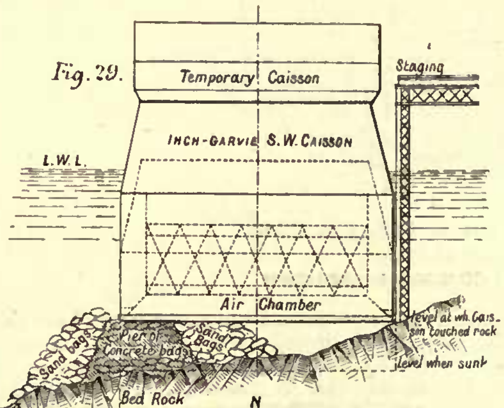


Fig. 30

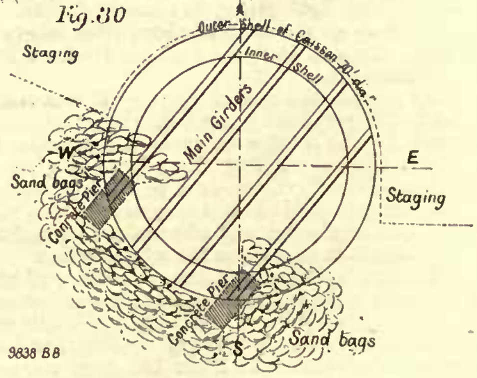


Fig. 27.

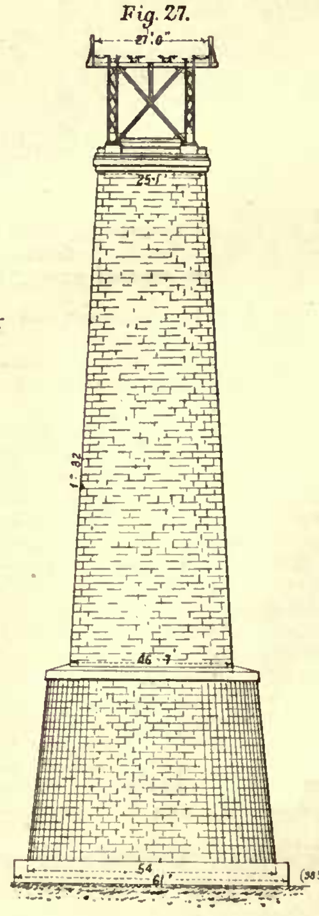
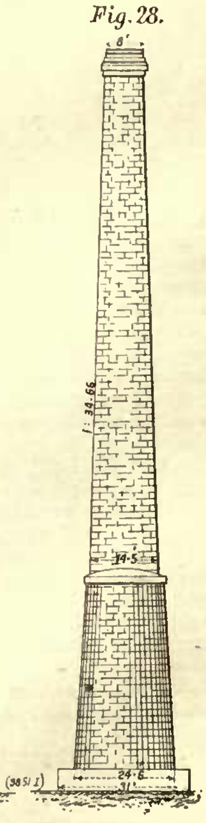


Fig. 28.



over a tide, a good deal of time was lost, but there was no charge for the sand.

Water.

Fife.—On the Fife shore the water required was drawn from the mains of the Dunfermline, Aberdour, and Burntisland water supply; but this supply becoming scarce, the contractors were obliged to construct a storage tank above North Queensferry.

Inchgarvie.—As already stated, no water was found on Inchgarvie, and, after some trials with condensers and filters, it was decided to use the lower 5 ft. of the holds of two of the steam barges as water-tanks. A large water-tank was set up on Inchgarvie, and the water was forced from the holds of the steam barges into the tank by means of pulsometers, the latter being worked by the steam of the barges' boilers. The water was taken from either the North Queensferry or South Queensferry supply, and this work was generally performed during the night by one or two barges, there being thus a steamboat available all night in case of emergencies.

Drinking water was supplied to the people on Inchgarvie in iron boxes encased in wood, holding about a cubic yard—the water being always taken from the Dunfermline mains for this purpose.

South Queensferry.—On the south shore the water was drawn from the pits of the Dalmeny Shale Works for boilers and other general purposes; but it proved too dirty, and some rough filter-beds of gravel had to be constructed to pass it through. Thence it was forced by pumps to an overhead tank set about 60 ft. above the level of the works and shops. This water was conducted in pipes down the incline to the jetty, and, in various leads, all over the works. For drinking purposes another supply pumped from the sandstone was available; but it proved very intermittent, and at times failed altogether. In the summers of 1886 and 1887 a water famine occurred at South Queensferry, and this was met by the contractors placing large iron tanks at the town harbour and sending a steam barge down the Firth to a place called Starleyburn, seven miles away, where a plentiful supply of water could be got. This was forced into the tanks, and could be drawn upon by all free of charge. In 1887 the united parishes of Kirkliston, Dalmeny, and South Queensferry arranged for a supply of water from the Pentland Hills, and this new supply is both plentiful and of first-rate quality, and has been running since the summer of 1888.

Cement.

The cement used exclusively was Portland cement manufactured on the Medway. This also came by water, but required to be stored for a specified number of days before it could be used. The contractors purchased an old hulk—called while in its prime the Hougomont—in which ten to twelve hundred tons could be readily stored. It was moored off Queensferry, and the ships bringing cement from the south were moored alongside and discharged. From this ship the cement was brought ashore and stored in such quantities as might be required at any time.

Subsequently the Hougomont was moored close to the west side of the South Queensferry jetty, and thus a more direct and speedy communication established. While the caissons were being sunk at Queensferry a large number of foreign workmen were lodged on board this hulk, and when, shortly after new year, 1886, an epidemic of small-pox broke out at Queensferry, the ship was towed round into Port Edgar, and moored in an isolated position, and converted into a small-pox hospital. As such it proved of signal service in speedily stamping out the disease.

Cement Tests.—The cement is described in the specification to the contract as having to be of the best quality and ground so fine that the residue on a sieve containing 50 divisions on the inch, equal to 2500 meshes per square inch, should not exceed 5 per cent. by weight. It had to be kept in a dry store, and was not to be used until a certain number of samples out of every cargo had been tested. Neat cement was not to be set within less than one hour. The weight had to be between 112 lb. and 116 lb. per bushel.

For tests, the cement to be mixed with three times its weight of sand which has been passed through a sieve of 400 meshes but retained upon one of 900 meshes to the square inch (20 divisions and 30 divisions to the lineal inch). About 10 per cent. of water had to be added, and briquettes made, which were to be put into water after twenty-four hours and remain in water twenty-five days, when they had to bear a stress of not less than 170 lb. without breaking. For briquettes of neat cement the breaking stress after four days had to be not less than 300 lb., and after seven days to be not less than 400 lb. per square inch.

A few tons of quick-setting or Roman cement were used in making good the joints of the circular iron cofferdams or caissons for the Inchgarvie north piers. This cement is not very strong, but if the joints are well packed with bags of clay puddle and loaded with stones they answer the purpose of keeping the water out for a while. If all preparations are made beforehand, Roman cement can be used in a plastic state, and is thus very useful to divers working under water; but all the work requires to be done very quickly.

Mortar.—The mortar used in the masonry was in the proportion of one of cement and one of sand in the foundations, where rubble-work was used, and one of cement to two of sand in the piers. The pointing in the joints of the granite blocks was done in pure cement.

Of the other materials used, except the steel, it may be as well to state here that timber in baulk was brought from Grangemouth, ten miles up river, where it was rafted and towed to the works wherever required.

Planks, battens, and boards were brought from the same place in lighters.

Hardwood, such as oak, beech, and ash, used for packings and other temporary purposes, was got in the neighbourhood and dealt with at the saw-mills.

Coal and coke for the three main piers were brought in barges—mostly from Charleston, close by; but for the shops and yards they were brought by rail.

Creosote oil for the Lucigen lamps, and rivet and other furnaces, came in specially constructed tanks by rail.

Commencement of the Permanent Work.

The positions of the four main piers on Fife being fixed at an early date, a beginning was made with the excavation of the rock upon the site of the two north piers. The natural bedrock of whinstone rose here to a level of from 10 ft. to 20 ft. above high water, and excavation had to be made to the level at which the foundation or holding-down bolts started—namely, at 7 ft. below high water. The rock was then levelled with rubble masonry and the building of the granite courses commenced.

Excavation was also started upon the site of the north cantilever pier at a level of about 21 ft. above high water, and upon viaduct piers, 10 and 11, at 25 ft. and 22 ft. above high water respectively. These three piers stand on high ground, while piers 12 and 13 were placed at the bottom of the ancient quarry, and were founded at level 7 ft. below high water. The foundations of the abutment upon the hillside was commenced somewhat later at level 92 ft. above high water. All the piers on the Fife side are founded on the solid whinstone rock, with the exception of piers 12 and 13, these being partly on whinstone, partly on freestone. All the viaduct piers being on land no cutwaters were built. The rock after being cleaned and examined, and worked roughly into steps where necessary, was levelled up with concrete and a bed of concrete laid on from 4 ft. to 11 ft. in thickness—this bed projecting all round the granite masonry some 2 ft. Upon this concrete foundation the first course of granite was set, the form of the piers being rectangular and the curved batter of the pier starting from the bed. (See Plate VIII.) Piers 10, 11, 12 and 13 were built to level 37 ft. above high water, and left, pending the construction of the girders.

Generally about Cofferdams.

In the description of the pier foundations, frequent use is made of the terms caisson and cofferdam, and to those not conversant with foundation work in water a short explanation may be acceptable. A cofferdam or caisson may be described as an enclosure in water for the purpose of laying dry the space enclosed, or, at any rate, of preventing a flow of water through it. In soft ground this is done by driving a double row of piles at a distance of from 2 ft. to 4 ft. from each other, and by continuing to drive piles between those already placed until a double timber wall exists all round. Sluice doors or valves are placed so as to allow the tide to flow in and out. The single timber piles are held together by longitudinal timbers being placed on each side and bolted through, and stays or struts are placed between the walls and across the inner space in all directions to give stiffness and resistance to the water pressure from without. The space between the double walls is now cleaned out as well as can be done, and clay puddle is filled into this space and trodden down hard or pressed down by other means, and this is carried on until the whole space is filled up to and beyond half tide or full tide as the case may be. The sluices can then be closed and the water pumped out from the enclosure, and the bottom upon which the foundation is to be placed can be examined, and all necessary excavation made. It depends partly upon the hold the piles have taken of the ground, partly upon the external forces acting upon the timber-walls—namely wind and waves—whether or not the construction of a whole tide dam is advisable. In a whole tide dam, if tight at bottom, when once the water has been pumped out, the work of excavation—of laying the foundation and building a pier or wall—can be carried on without interruption to the end. In the case of a half-tide dam, the space enclosed can only be pumped dry after the tide outside has fallen below the level of the clay puddle wall, and the water requires to be admitted so soon as the tide has turned and is rising again up to that level. Work in a half-tide dam is termed tidal work. When working on rock this mode of forming an enclosed space by driving piles is not admissible, and other means must be found to keep the water

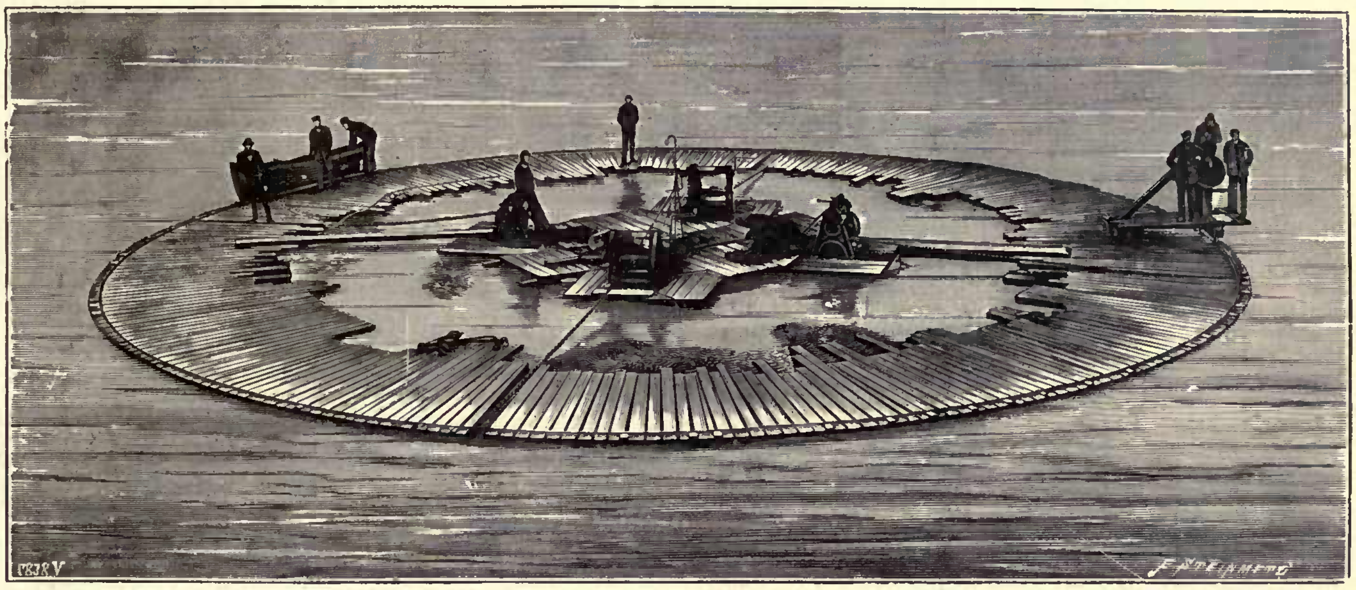


Fig. 31. Raft used for survey of foundations.

out, one of which will be described below. In some cases, whether working upon soft ground or rock, it is not absolutely necessary to lay the bottom dry in order to excavate or to inspect the ground—the latter being done by means of divers and the former by dredging or otherwise. The object of such a dam is to arrest the flow of any current through the caisson while the foundation is being laid, and to deposit the material of which the foundation is to consist—most generally concrete—by lowering it through the water in boxes or skips, the bottoms of which are provided with hinged doors.

Finally, if instead of a caisson open at top, the caisson is covered in like a bell or gasholder, and the water is forced out by forcing air in, thereby allowing the workmen to enter and excavate in the dry, it is called a caisson worked by the pneumatic process. In this manner the deep-water foundations of the circular piers were executed, as will hereafter be described, in the case of the two south piers, Inchgarvie, and the four Queensferry circular piers.

Inchgarvie North Circular Piers.

On Inchgarvie the site of the two north or shallow piers being wholly submerged at high water, and about one-half in the case of the north-east, and three-fourths in the case of the north-west pier, submerged also at low water, the preliminary work was tidal, and between spring tides no work could be carried on at all at this place. When it is considered how exposed the position was there—the work having to be carried on upon a narrow ledge of rock attacked by wind and waves from all sides—it will be understood that the progress could not be very rapid. The conditions of the contract here required that the rock should be excavated in steps, and that the rubble masonry comprising the foundation of the circular granite piers should be bound by an iron belt 60 ft. in diameter and 3 ft. deep; the highest portion of the rock upon which this belt rested to be 2 ft. below low water; the belt, or at any rate a part of it, to be brought down to form a protection for the foundation rubble masonry upon the lower steps.

It was therefore decided to cut a chase 8 ft. wide (3 ft. to the inside and 5 ft. to the outside of. the 60-ft. circle) out of the rock where it was higher than 2 ft. below low water, to make the 60-ft. belt of three thicknesses of $\frac{1}{2}$-in. plate, and to carry the centre plate downwards, after it had been cut, in such manner as to fit as nearly as possible the natural contour of the rock. (Fig. 21.) A light staging was, therefore, erected above high water, the correct centre of the pier placed upon it, and by means of a trammel-rod 30 ft. in length, from the end of which a pointed sounding-rod was suspended, a correct reading was taken every 6 in. on the circumference of the 60-ft. circle, after a diver had been round to clear out any loose stones lying in the line, or picking off any sharp points projecting. These readings were plotted and the centre plates cut to it. In the mean time work had been done upon the chase, and, when nearly cut down to the right level, the belt was put together on the staging exactly above the site of the pier. The plates projecting downward, and forming the shield, were stiffened by T bars vertically over the butts, and, where required to be carried down to a considerable depth, as in the case of the north-west pier, they were further stiffened by horizontal circular girders and stayed to the rock by bars of angle-iron. The whole belt was now rivetted up, and, when ready, received two coats of red-lead paint, and was lowered down by means of hydraulic jacks into position. (Fig. 22.)

The top edge of the 3-ft. belt was then levelled all round, and corrected where necessary. A heavy angle iron, 6 in. by 6 in. by $\frac{7}{8}$ in., ran round the inside of the 3-ft. belt, and upon this was now set a single tier of temporary caisson, 10 ft. in height, and consisting of fourteen segments of about 30 cwt. each in weight. This helped to keep the belt down to the rock, and a number of heavy blocks of stone were placed on the top of the caisson for the same purpose. A sluice door in the lower part of the caisson was kept open to admit of the tide flowing in and out.

Steps were now taken to make good the joint between the 3 ft. belt and the shield and the bedrock. This was done in the following manner: A number of concrete bags, about 14 in. by 30 in., and 8 in. to 9 in. thick, were prepared and passed down to a diver, who laid them round the outside of the belt at a distance of about 4 in. A second row was next laid round the outside of the first row, and tolerably close up, the space between the two being made up by clay puddle well stamped down. Any split, or hole, or crevice in the rock was also filled with clay. Upon these two lower rows, other bags were now laid crosswise; upon these, two rows lengthwise, and a fourth row crosswise on the top, which was laid close up to the belt. This was done in sections of about 15 ft. to 16 ft. length all along the shield, but round the outside of the treble belt only two bags deep were laid. On the inside also a single row of clay bags, backed by a row of concrete bags and loaded with stones, was laid round the complete circle. Cement grout, without intermixture with sand, was now prepared and passed down to the diver—but only at slack tide, high water, or low water—who lifted off one or more of the top bags and poured the grout into the narrow space left, until it overflowed. He then replaced the bag and proceeded to the next division until all was done. Forty-eight hours were allowed to elapse for the setting of the cement; the sluice valve was then closed, and the caisson pumped out gradually. When leaks were discovered, the diver descended to examine the outside, and, where necessary, cut out some of the grouting and replaced it by new.

As it was not considered that this cement joint would be able to stand the full pressure of the tide rise, the caisson or cofferdam was worked as a half-tide one, it having to be pumped out every tide as soon as the water had fallen below the top edge of the temporary caisson. In addition to the hydrostatic water pressure, the caisson had to stand the heavy seas thrown against it, whether coming from west or east. Under these circumstances, it was often considered advisable not to pump out the cofferdam, but leave the sluices open and allow the tidal flow free access. Under such conditions, it will be easy to see that, during a season of bad weather, much delay could not be avoided, and though the work of excavation had been commenced in the summer of 1883, it was not till the middle of April of the following year that the first rubble masonry could be laid in this pier. In working the excavation, no blasting was done within $1\frac{1}{2}$ ft. of the iron belt, but the rock was quarried up to within 6 in. and rubble then built in at once. Any steps cut in the deeper portion were invariably at least twice as broad as they were deep. The deepest point to which excavation had to be carried in this pier was at 8 ft. below low water.

The cofferdam or caisson for the north-west pier, Inchgarvie, was done in the same way precisely as described for the north-east, only that, owing to the experience gained by the divers and other men engaged upon the work, the progress was much more rapid.

In the north-west pier the depth of the shield was 15 ft. below low water, and extended to nearly one-half of the circumference. There were, therefore, in addition to the vertical T bars which covered the butt-joints of the shield-plates, three horizontal circular girders, carried at a distance of 4 ft. 6 in. from each other, and from these a number of horizontal tie-bars with cross-bars at the ends were carried radially and level to the rock opposite and pinned to it, and afterwards built into the solid rubble masonry. (See Fig. 22.)

This mode of making the joint between the rock and the iron belt was simple and quite effective. Most of the leaks were due to natural crevices in the rock, running from the inside to the outside at a considerable depth. These were circumvented by building small clay dams round, and leading the water by a shoot to a pump. Leaks were also caused by the action of heavy waves running up to the temporary caisson at low water with great violence, and shaking the whole fabric.

The whole of the north-east pier was built in a half-tide caisson, as the work was not pressing; but in the case of the north-west pier, so soon as the rubble masonry inside had been brought up to low-water level, a second tier of temporary caisson was added, and the work could then be carried on at all states of the tide. While tidal work was carried on in these two cofferdams, the amount of water which had to be pumped out every tide was 250,000 gallons in the one case, and 340,000 in the other. The time occupied was 50 to 55 minutes, but work was, of course, commenced so soon as the higher parts were laid dry. For pumping out smaller quantities of water collected through leaks, pulsometers or small centrifugal pumps were used. The temporary caisson is shown in Plate VII.

A statement of the time occupied in building the foundations of these two piers is given in Table No. II.

TABLE No. II.—Progress of Work on Inchgarvie Piers.

——	North-East Caisson.	North-West Caisson.
Rock excavation commenced	June 22, 1883	January 13, 1884
Lowest point of foundations	26 ft. below high water	33 ft. below high water
Caisson and shield ready for lowering	February 29, 1884	September 10, 1884
Joint between caisson and rock made good	April 2, 1884	October 17, 1884
Caisson pumped out first time...	April 5, 1884	October 20, 1884
Rubble masonry in foundation commenced... ...	April 16, 1884	October 24, 1814
Foundation finished to low water	June 1, 1884	December 20, 1884
First granite laid	June 2, 1884	December 23, 1884
Pier completed	November, 17 1884	March 18, 1885

Fife South Circular Piers.

As the two south piers on Fife were also situated on the sloping face of the rock, and required excavation at different depths, a somewhat similar course was followed in the construction of the cofferdams or caissons, but with one important difference. In the case of Inchgarvie the caissons were set on the rock, and secured to it, as far as possible, by weighting them, and the joint was made good previous to any blasting of rock near the 60-ft. circle being done, except so far as the excavation of the circular chase was concerned; while in the case of the Fife south piers, diamond-drilling plant under a sub-contract was employed to drill all over the area of the pier and blast the rock before any cofferdam or caisson had been put down. For this work an iron girder staging was erected over the piers, on which a traveller with running gear from end to end was placed. The depths to which the different steps in the excavation had to be carried was given, and holes drilled to these depths. When a number of holes were ready, they were charged with explosive and fired; but the rock was not removed at the time, and lay there in great shattered masses.

The consequence was that when it was attempted to place caissons with projecting shields to fit the contour of the rock, the leaks were of such a nature as to defy any pumping power then at hand.

The Fife south-west pier, in which the deepest part was 7 ft. below low water, and in which only a very small portion lay below the level of the circular chase 2 ft. below low water, could be managed with some little difficulty; but in the south-east pier, where the shield had to be carried to 19 ft. below low water, it became necessary to construct a puddle clay dam round the outside of the caisson with piles heavily shod and driven into the débris of broken rock. Even then the difficulty could only be overcome by collecting together the water from a number of leaks, and by means of powerful pumping machinery to get the upper hand of it. Rubble masonry was then built in all places where running water could be kept off, and the leaks were thus gradually hemmed in, and finally stopped by pouring cement grout into these places at slack water and with the sluices open, in order that no water might be forced through the grouting before it had set.

A large diving bell, with air-lock and the necessary machinery to move the bell all over the area of these piers, had been constructed, as it had been intended to form the foundations of concrete deposited through the water by hopper-bottomed skips; but as it was subsequently decided to have the foundations of rubble masonry instead, it became

necessary to lay the bottom dry, and the diving bell was never made use of.

The north piers on Inchgarvie and the south piers on Fife are founded on the solid whinstone rock.

Table III., given below, shows the time occupied in building the foundations of the four circular piers on Fife, the depth to which the foundations were carried, and other particulars.

TABLE No. III.—Progress of Work on the Four Circular Fife Piers.

	Fife Circular Granite Piers.			
	North-West.	North-East.	South-West.	South-East.
Excavation commenced	August, 1883.	Feb., 1884.	August, 1883.	Nov., 1883.
Lowest point of foundations	7 ft. below h.w.	7 ft. below h.w.	25 ft. below h.w.	37 ft. below h.w.
Rubble masonry in foundation commenced	Nov., 1883	March, 1884	June, 1884	March, 1885
Foundation finished to low water ...	Nov., 1883	April, 1884	June, 1884	May, 1885
First granite laid	Dec., 1883	April, 1884	June, 1884	June, 1885
Pier completed	Sept., 1884	Sept., 1884	Jan., 1885	August, 1885

South Approach Viaduct Piers.

On the South Queensferry shore the foundations of piers 3, 4, and 5 were first started, as they were all dry at low water. These three piers are founded on the freestone rock prevalent in ridges all along this shore. Tidal work had to be resorted to without any protection by cofferdam or caisson, and all that was required was to remove the soft or rotten portions of the rock and cut flat steps into any sloping faces met with. The hollows were then levelled up with concrete, and upon this a concrete base was laid enclosed by planking. When this had properly set the granite masonry was at once begun. The concrete base was 61 ft. long by 31 ft. wide, and was the same for all viaduct piers from 3 to 9. The thickness of this concrete foundation varied according to position, from 4 ft. in the shore piers to 11 ft. in No. 9 pier. Piers 2 and 1, as also the abutment, were situated on the hillside. The first was founded on the freestone rock; but the other two were placed on a stiff blue clay of sufficient solidity. Pier 6 required the construction of a cofferdam, the bottom being rock with a thin layer of gravel and clay. Owing to this the cofferdam could not be carried to more than half-tide, the difficulty being to get the piles to hold. A great deal of trouble was experienced with this foundation through the want of a tight joint at bottom; but it was, of course, only a matter of patience and perseverance. The foundation of pier 7 also caused some trouble owing to the same difficulty at bottom, and a half-tide cofferdam had to be used; but in the foundations of piers 8 and 9 the layer of clay at bottom was of sufficient thickness to allow good piling to be done, and whole-tide cofferdams could be constructed. Pier 7 is founded on the rock, but piers 8 and 9 are founded on the hard clay.

TABLE No. IV.—Particulars of Foundations for Viaduct and Cantilever Piers, and Nature of Ground.

For General View of Piers see Plate III., Figs. 1 and 2.	Level of Foundations referred to High Water.	Nature of Ground.
South abutment	109 ft. above	Blue clay
Approach viaduct pier 1	32 ft. ,,	,,
,, ,, 2	7 ft. ,,	Freestone rock
,, ,, 3	13 ft. 6 in. below	,,
,, ,, 4	14 ft. ,,	,,
,, ,, 5	17 ft. ,,	,,
,, ,, 6	22 ft. ,,	,,
,, ,, 7	30 ft. ,,	,,
,, ,, 8	32 ft. 6 in. ,,	Hard clay
,, ,, 9	38 ft. ,,	Boulder clay
Cantilever end pier, south	33 ft. 6 in. ,,	,,
,, ,, north	21 ft. above	Whinstone rock
Approach viaduct pier 10	25 ft. ,,	,,
,, ,, 11	22 ft. ,,	,,
,, ,, 12	7 ft. below	Part whinstone
,, ,, 13	7 ft. ,,	Part freestone
North abutment	92 feet above	Whinstone rock

The south cantilever pier required a cofferdam of abnormally large proportions and of great strength, for the base upon which this great masonry pier had to be raised was not less than 115 ft. long by 60 ft. wide. It was at first divided into halves by a double row of piles with puddle clay filling; but, after a good portion of the concrete base had been laid all round the sides of the dam, this partition was cut down, the piles being sawn off flush with the bottom and the concrete base carried right across. In this pier the boulder clay at bottom was found nearly dry and extremely tough to handle, and it gave an indication of the ground into which the large caissons would have to be sunk.

Table IV., given below, shows the levels at which the foundations were started of all the viaduct piers from 1 to 9, of the south cantilever pier, the north cantilever pier, and the abutment, as also the nature of the ground under foundations.

Figs. 23 to 28 show views of the cantilever end pier and the viaduct piers, with the principal dimensions. The cutwaters with a coping of dressed granite reach to the same height above high water as the circular piers, namely 18 ft., and up to this level all the piers from 3 to 9 were built with a hearting of concrete; above this level the granite was backed by masonry of Arbroath rubble in cement carried up to the top. The hearting in piers 1 and 2 was of concrete up to the level at which the viaduct girders were erected—namely, at about 47 ft. above high water, from this level to top they were, like the other viaduct piers, built with a hearting of Arbroath rubble.

To facilitate the building of these piers, staging was erected alongside and connected with the jetty, and cranes were set up to lift the granite blocks from the jetty adjoining and deposit them in their places. All materials were brought along the jetty, where also the mortar was prepared and the concrete mixed. Two courses of granite were generally laid, and the hearting of concrete filled in. The mortar used consisted of one part cement and two parts sand.

The concrete consisted of 27 cubic feet, or 1 cubic yard of broken whinstone, $5\frac{1}{2}$ cubic feet of cement, and $5\frac{1}{2}$ cubic feet of sand, mixed dry by hand and then charged into a concrete mixer where the water was added. From the mixer it was delivered into barrows and tipped where required.

All the south viaduct piers from 3 to 9, and the south cantilever end pier, were built up to a level of 18 ft. above high water, and further work upon them had to be delayed until the girders had been erected and rivetted up, and were ready for lifting. The dates relating to the building of the piers, the raising of the girders and the quantities of materials used, are given in a summary on another page.

Piers 1 and 2 were carried up to level 47 ft. above high water, and the girders built at that level. The south abutment was raised to 119 ft. above high water, and the girder erected at that level on staging reaching close up to No. 1 pier.

Preliminary Work in Connection with the Inchgarvie South Piers.

It has already been mentioned in the description of the Inchgarvie staging, that places were prepared for the reception of the two south caissons presently to be brought across from the Queensferry jetty.

In order to obtain at an early date a correct idea of the contour of the rock upon the sites to be occupied by the two south piers on Inchgarvie, a circular raft was constructed of timber balks decked for about 10 ft. round the outer circumference, with 3 in. planking. The raft is shown in Fig. 31. It was made sufficiently strong to resist the action of the waves in an ordinary breeze of wind, or to bear, if necessary, the strain of being beached on shore in case stormy weather should set in. It was a little under 70 ft. in diameter, and the surface of the planked space was 6 in. above water. Large mooring blocks were laid at some distance on

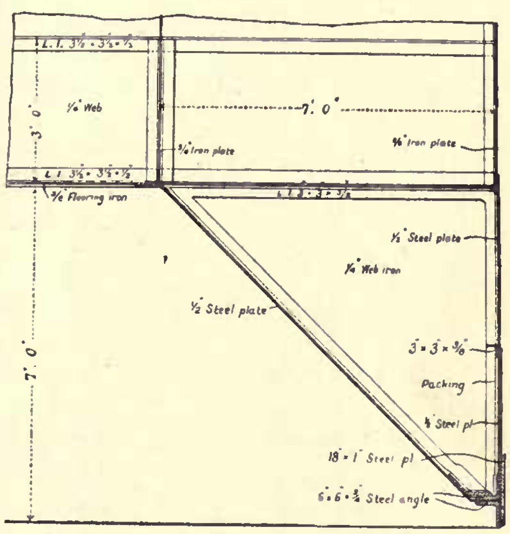


Fig. 32. Cutting edge of caisson.

three sides, the fourth being attached by cable chains to some of the iron columns of the staging. Upon the raft four crab winches were placed, by means of which either of the mooring chains could be hauled in or slackened. The raft could thus be easily placed in any desired position within tolerably wide limits. A central staff was fixed upon the raft, and about a foot from the outer edge a ring of gas-pipe was laid down upon which the grooved wheels of a carriage ran true to the centre of the raft. A drum was placed upon the carriage, somewhat overhanging the edge of the raft, and upon this drum the sounding line was coiled. This consisted of a fine steel wire and a long weight weighing about 60 lb., with a point at bottom, feet and inches being marked upon the wire by copper tags attached.

Two theodolites—one in the centre line of the piers longitudinally on the iron staging, the other on a masonry pier at right angles to the centre line, but in line with the centres of the two south piers—were stationed to check the position of the centre of the raft every few minutes, while alterations in the tide level were observed on two tide gauges, and recorded. Owing to the heavy current running at this point—both during ebb and flood—the raft could not be held in position with any degree of accuracy, nor could the sounding line be kept plumb in spite of the heavy weight attached. Soundings were therefore only taken during slack water—that is, for about an hour before and an hour after high water or low water.

After the actual contour of the rock, on and within the two 70-ft. circles, had been taken, the raft was shifted about in various directions and further soundings recorded, the exact position of

THE PNEUMATIC CAISSONS; QUEENSFERRY.

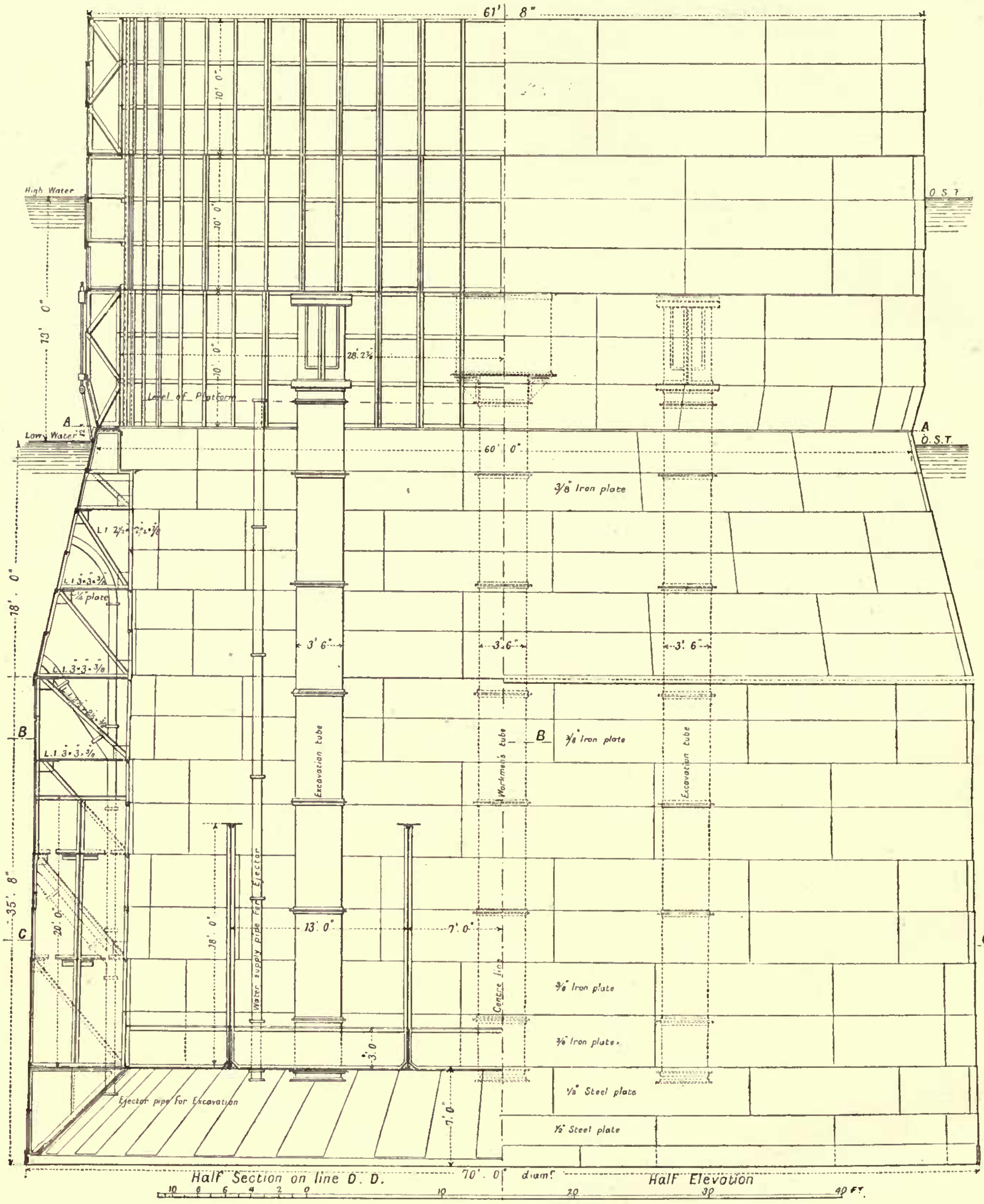


Fig. 33.

the centre being always fixed by the two theodolites reading angles from fixed stations. The whole area for about 40 ft. or 50 ft. round the two caissons was thus sounded, and a very fair idea of the contour of the bottom obtained. About 3000 soundings were thus taken, representing a large amount of work and trouble with the sounding gear, the mooring chains, the winches, and last, though not least, with rough weather, and distortions thereby produced in the raft itself.

The raft was also used for fixing the guide piles or columns against which the caissons would come to lie, and, as a precautionary measure, the centre was set 1 ft. up the slope of the rock, as it was tolerably certain that during the sinking operations the caisson would slide away from the newly cut face.

As soon as the soundings had been taken, and the guide columns fixed for the reception of the caissons, heavy mooring blocks were laid down to the south-east, south, and south-west, with heavy cable chains attached, the ends of which were temporarily secured to the staging. Two stout wire hawsers were also prepared to pass round the caissons as soon as they would be placed in position.

To hold the caissons with some amount of security when once they would take the ground, and give them a good bearing all round the edge, it had been decided to place a large number of sandbags upon the rock, and bring these up to the same level —and somewhat above even—as the highest point of rock the cutting edge of the caisson would be likely to touch. In order to still more securely fix this bed of sandbags, two rectangular piers were built up first of bags filled with concrete, and these were placed (see Figs. 29 & 30) opposite the highest point of the rock on the circumference of the 70-ft. circle. The concrete was of good strength, there being 27 cubic feet of stone to 4½ cubic feet of cement and 4½ cubic feet of sand. It was mixed dry, slightly wetted, and at once filled into bags. About twenty-six of these went to a yard, and they were put into boxes with hinged bottom and lowered down by a steam crane and emptied. They were put together by a diver, and, when a couple of feet of pier had been built, a number of sandbags of much larger size were put all round it to keep it in place and prevent the tide from washing out the cement. When the concrete piers had been completed, the remaining space under the cutting edge was laid with sandbags, except in two or three places where channels were left through which the air could escape, and through which also the sand-bags and other débris could be pushed down the rock during the sinking of the caissons. In two places well within the air-chamber, and near where the centre of the caisson would come to be, two piers of sandbags were built up upon which the ceiling of the air-chamber would be supported.

It remained now to lay down the pipes for the

THE PNEUMATIC CAISSONS; QUEENSFERRY.

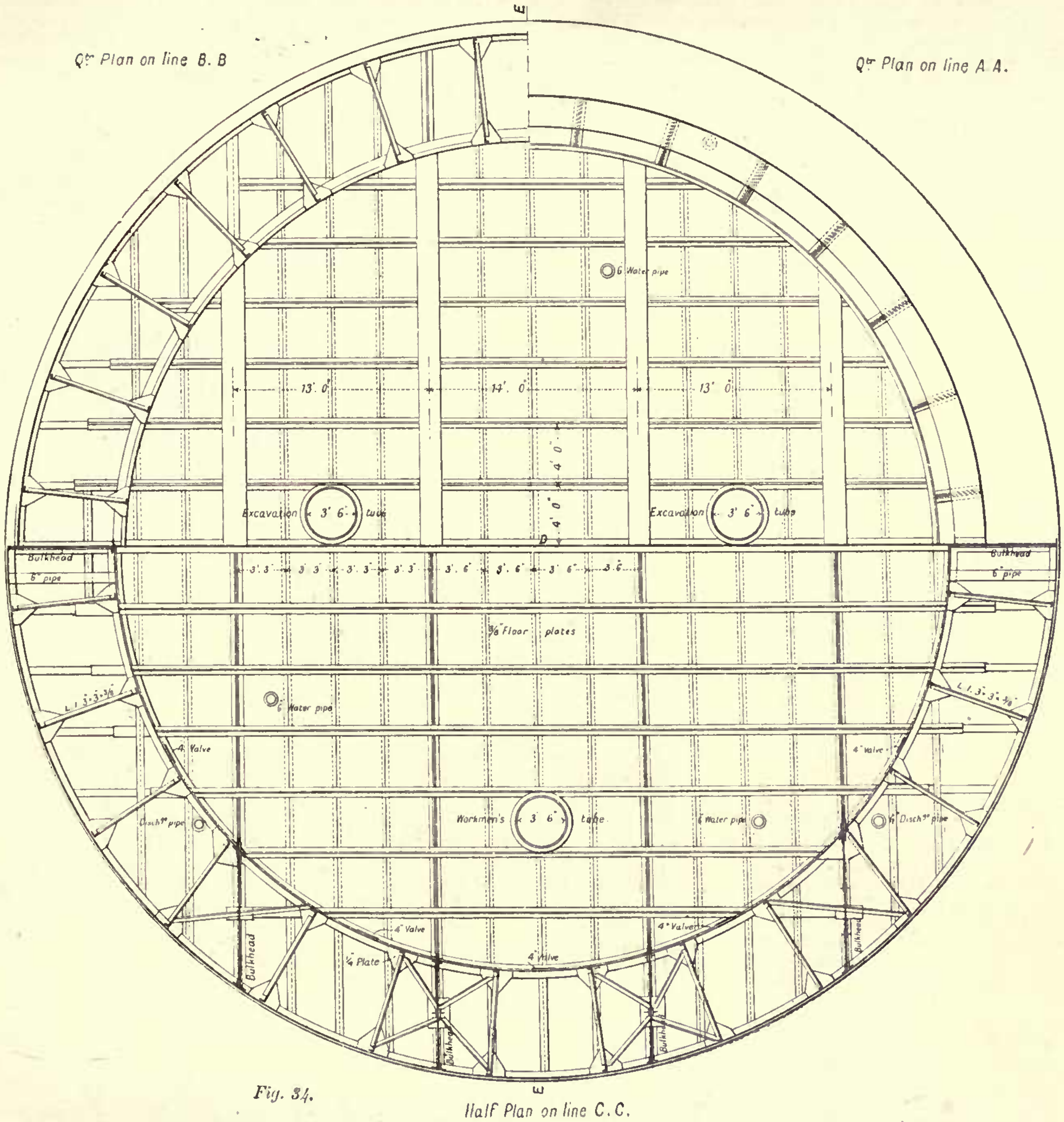


Fig. 34.

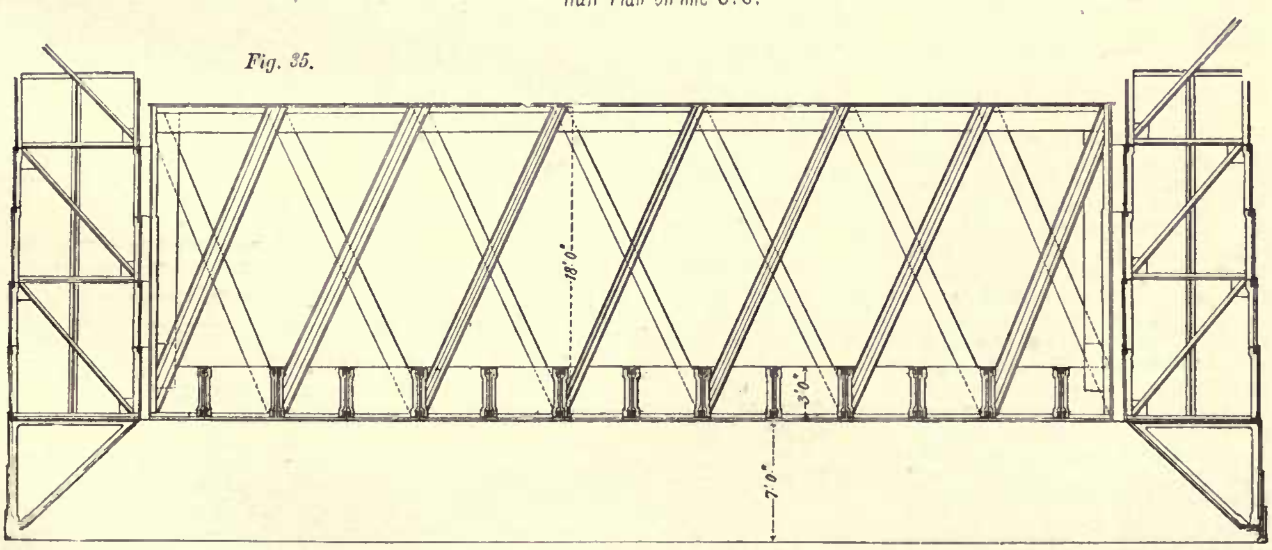


Fig. 35.

supply of air and water, and the electric light cables for immediate connection with the caissons as soon as they should be moored in place.

Preliminary Work in Connection with the Four Queensferry Caissons.

Over the area to be occupied by these four circular piers, and to some extent outside and round it, a number of soundings were taken to ascertain the depth of water, of mud, of silt, of soft clay, and of hard clay. These data are given in another place. The T head of the jetty, which had in the mean time been completed, left four corner spaces free for the reception of the caissons, and strong timber dolphins of treble and quadruple piles were placed on three sides of the space left. As the tide currents are not nearly so strong here as on Inchgarvie, and as the caissons would almost immediately touch the soft ground during low water, the danger of their getting away was much less here, and no outside moorings were therefore provided, but strong chains fixed to the piles, and ready to be attached to lugs rivetted to

the caissons, and stout ropes and wire hawsers to pass round them, were kept in readiness.

Air compressors, electric light machinery, overhead water tanks, pumps to supply the same, steam cranes, and other plant, were got ready, and large quantities of broken stone, cement, and sand were stored close by for use. Water pressure at 1000 lb. per square inch was brought down the incline from the accumulator on the top, and conducted to the end of the jetty.

The Pneumatic Caissons.—The six caissons which were sunk by the pneumatic process were mainly built of wrought iron, and were in the first instance constructed and put together by Messrs. Arrol Brothers, of Glasgow—namesakes, but otherwise in no way connected with Messrs. W. Arrol and Co., of Dalmarnock Iron Works, Glasgow. These caissons were taken to pieces again and sent to Queensferry to be built up and rivetted, as hereafter described.

Description of the Caissons.—The four caissons of the Queensferry group are all of one design, differing only in height. There are two shells, carried up at distances varying from 7 ft. at bottom to 4 ft. 6 in. at top from each other. (See Figs. 32, 33, 34, 35.)

The two Inchgarvie caissons, although externally the same in appearance, differ in so far as the inner shell is only carried up as far as the top of the cylindrical portion, being replaced above that by a backing of Staffordshire blue bricks built in cement, which was carried up in proportion as the caisson was sunk below low water. (See Fig. 36.)

Generally speaking, the caissons are made up of two parts—the cylindrical and the taper part. The cylindrical portion is of varying height, with a slight taper upwards to facilitate the sinking. This portion is 70 ft. in diameter, and above it is the taper part, which is 24 ft. high in all cases, and terminates with a diameter of 60 ft. at top.

The lower, or so-called cutting edge of the caisson, is stiffened by a stout double angle and by a broad steel belt, 18 in. wide, and 1 in. in thickness.

At a height of 7 ft. above the cutting edge an air-tight floor is formed which extended over the whole area up to the outer skin or shell. From this floor upwards, started the inner shell of the caisson, about 56 ft. in diameter; and here also, but downwards, started the sloping plates, which terminated at the cutting edge, and which were backed and held by a number of triangular brackets set against the floor to one side and against the outer shell to the other. A circular space of triangular section was thereby formed, access to which was had by manholes cut into the floor between every two brackets. Under the floor a space was thus left of the form of a truncated cone 70 ft. at bottom, 56 ft. at top, and 7 ft. in height, which was called the air-chamber or working chamber. Its function was to act as a diving-bell for the purpose of gaining access to the bottom of the river and carrying on the necessary excavation over the area thus made accessible. The triangular space surrounding the air-chamber was called the shoe, of which the lowest part, as already said, formed the cutting edge.

The roof of the air-chamber was supported by four strong lattice girders 18 ft. in height, and reaching from side to side of the inner shell, but being carried through to the outer shell by means of bulkheads or plate diaphragms set between the two shells, and rivetted through with the end posts of the large girders. At right angles to these latter were carried plate girders 3 ft. deep, and spaced 4 ft. apart, centre to centre, all over the ceiling of the air-chamber. The floor plates were so arranged that their joints, where it could be done, were butted immediately under the centres of these girders, the bottom flanges of which acted as covers on one side, while there were covering flats on the other side.

Between the shells, the stiffening was obtained by circular lattice girders, which consisted of angle rings attached to both the inner and outer shell at every plate joint, and of angle bars set radially and attached to the angle rings by gusset plates, and also by inclined angle struts which passed from the angle ring attached to the inner shell to the next higher ring attached to the outer shell. The top of the caisson was formed of a horizontal circular plate girder upon which the temporary caisson was set and bolted down, the joint being made by india-rubber cording about 1 in. in diameter.

As already stated, the inner shell in the Inchgarvie caissons was not carried up to the top, but terminated with the cylindrical portion. To make up for the loss of strength a circular plate girder about 2 ft. 8 in. deep is carried right round at this place, similar girders being placed at the second plate joint below, and at every second plate joint above, all these circular girders being combined by vertical angles about every 6 ft. on the circumference. (See Fig. 36.)

bottom, forming the flanges. Two of these shafts were used for the removal of the débris of excavation, the other for the ingress and egress of the workmen. In the Queensferry caissons the shafts were pretty evenly distributed over the area of the working chamber, the reason being that in these caissons, as soon as they touched ground, work could be carried on all over the area at once. In

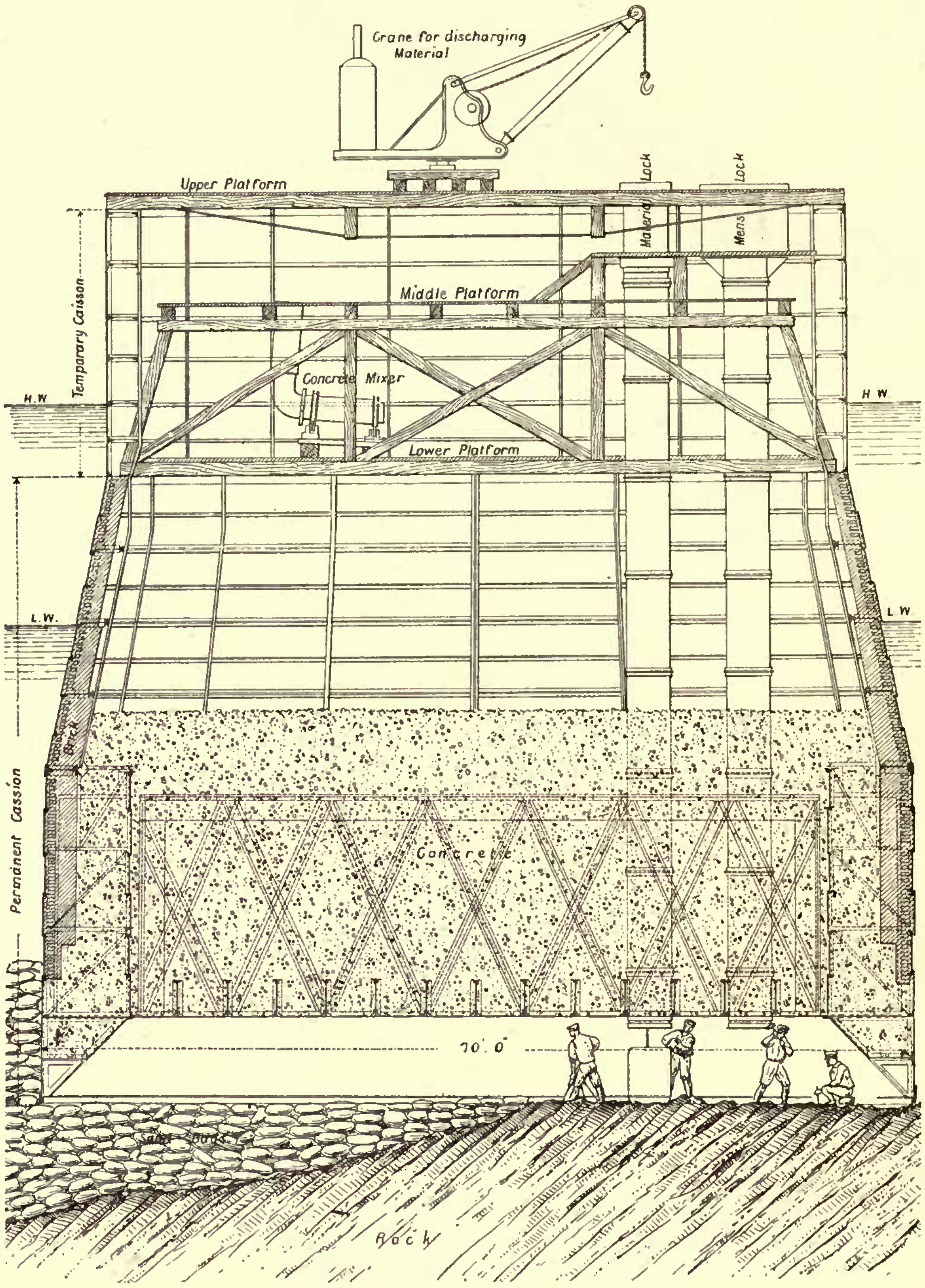


Fig. 36. Section of caisson at Inchgarvie.

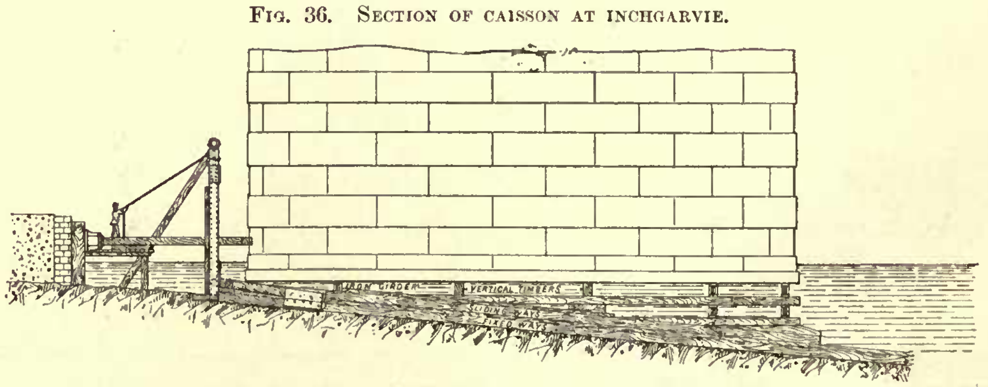


Fig. 37. Caisson and cradle on launching ways.

Three holes about 3 ft. 7 in. in diameter were cut into the ceiling of the air-chamber at convenient distances, and here were inserted three air-shafts, the lower edge projecting into the air-chamber about 6 in. They were made up of lengths of 8 ft. each, with an angle hoop rivetted on at top and

the case of the Inchgarvie caissons, only two shafts —one for men and one for material—were used, and these shafts were close together at one side, because most of the work there had, owing to the sloping face of the rock, to be carried on near the point where the cutting edge first touched the rock. In

addition to the air-shafts, a number of cast-iron pipes were fixed, reaching from the air-chamber ceiling to various parts of the outer shell, and these were used for the removal of silt and soft material, all of which, in combination with water, were ejected by means of a small quantity of compressed air being allowed to escape.

In the air-chamber itself, the main difference between the Queensferry and Inchgarvie caissons consisted in a different arrangement of the shoe.

In the former, the sloping plates were carried right down to the cutting edge, while in the latter they only went half-way down the slope, being then bent in a horizontal direction, and brought to the outside shell and then rivetted on. For the support of the lower remaining portion of the outer shell, strong brackets were fixed about 3 ft. 6 in. apart on the circumference, and these terminated at the lowest angle, which, with the 18-in. steel belt, formed the cutting edge of the caisson. This was done in order to allow the sinkers the fullest access to the rock immediately under the cutting edge, it being of the greatest importance that it should be undercut to the extent of at least 6 in. all round. The section of the Inchgarvie shoe is shown in Fig. 52.

It has already been stated that launching ways were laid down on the south shore to the east of the jetty. These timbers (Fig. 37) were laid on the natural slope of the ground, holes being dug at intervals which were filled up with concrete, and thus provided strong piers to carry the weight of the caissons. At the higher end of the timbers several trestles were set transversely, of such height as to keep the work out of the reach of the water. The tops of the trestles formed the platform upon which the construction of the caisson was commenced and carried on until about 25 ft. or 30 ft. of it, counting from the lower edge upwards, had been built. The weight was then about 300 tons. By means of hydraulic jacks the caisson was then slightly raised and packed, and the trestles withdrawn. It was then lowered down to within half a foot of the top of the launching cradle. This was made up of transverse girders laid on longitudinal timbers, which in their turn were laid on the timbers forming the launching ways. The top of the cradle was, of course, horizontal, and it was essential to support on it as large a portion of the ceiling of the air-chamber as could be reached, and also as much as possible of the lower or cutting edge of the caisson, which latter was also supported for the time being by a number of timber blocks placed on the ground.

Building of the Caissons.

In the building of the caissons, the general practice was to commence by laying down the bottom booms of the large lattice girders upon the timber trestles at the head of the launching ways, to bolt the 3-ft. cross-girders between them, and fix to both the floor-plates. Outside the trestles, any projecting parts of the caissons were supported from the ground by timbers. The plates forming the inner shell were next put on, and also the sloping plates forming the shoe, the two forming one joint with the floor-plates. All joints were rivetted up as far as possible by ordinary hydraulic rivetters, and meanwhile the bracings of the big girders were put on and the top booms laid on these, and more plates were added to the inner and outer shells. Upon the girders the first platform was laid down, and a hand crane set up as well as forges, concrete mixer, and other gear. By the time the caisson was about 25 ft. high—much of the lower work being then done—it was got ready for lowering, as already described. It was even then still accessible in the lowest portions soon after half-tide for further work and for making preparations for launching. Previous to this, all joints in the plates forming the ceiling—the sloping face of the shoe and the outside shell of the caisson—were carefully caulked to make a good water-tight job.

In all cases, previous to launching a caisson, the shoe and the whole space over the ceiling of the air-chamber were filled up with concrete, the latter generally to a depth of from 4 ft. to 6 ft. This not only acted as ballast, but it gave much stiffness to all the lower portion of the caisson, and produced a draught of from 9 ft. to 10½ ft. after it floated.

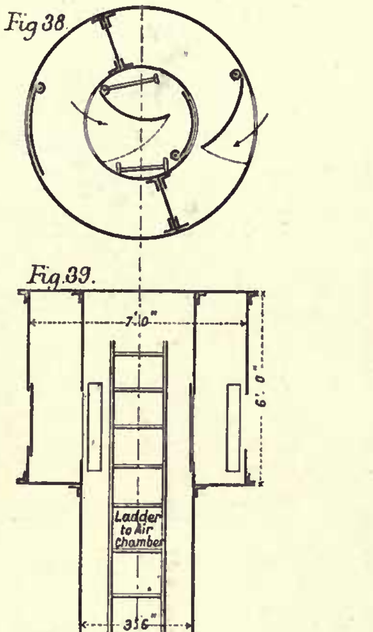
When finally the caisson had been built to the required height and weight, all the points of contact between cradle and caisson were carefully adjusted, and all the weight allowed to rest on the cradle, it being then ready to be launched. The cradle was loaded with pieces of iron to hold it down to the launching ways when the water lifted the caisson off its bearings and floated it away. The slope of the launching ways being about 1 in 11, it required a push from a 12-in. hydraulic jack, placed horizontally, to set the mass in motion, and this it did most effectually on all occasions.

The launching of these caissons took place generally at or near to the time of high water of spring tides, owing mainly to the shallowness of the shore in front of the launching ways—the caissons drawing from 9 ft. 6 in. to 10 ft. 6 in. of water at the time. As soon as afloat a tug-boat was attached and the floating monster at once towed to its final resting-place, or else to the end of the jetty, where conveniences existed for charging concrete into it and placing all the necessary machinery on board, as also the temporary caisson on top. Should any tide not rise as much as was expected, it was the practice to hermetically seal the air-shafts and other outlets from the working chamber and force air into the latter, in order to increase the buoyancy.

The first caisson—that for the south-west pier, Queensferry—was launched on May 26, 1884, the ceremony being performed by the Countess of Aberdeen, the Earl being at the time Lord High Commissioner to the General Assembly in Edinburgh. The last caisson was launched on May 29, 1885—the south-west Inchgarvie.

Fig 38.

Fig.39.



AIR-LOCKS.

The Temporary Caissons.—The temporary caissons, placed on the top of the permanent ones for the purpose of keeping the water out while the circular granite pier was being built, were of the same construction as already described in connection with the Inchgarvie north piers. (See Figs. 32 and 51.) The lower tier of caisson segments, in addition to the large number of small bolts which made the water-tight joint, had two long 2-in. bolts to each section of caisson, or twenty-eight bolts on the circumference. These bolts terminated at top in a screw thread with nuts, and at bottom in a long shackle, which grasped a lug rivetted to the outside of the permanent caisson. The temporary caisson was made large enough to allow space round the completed pier for the masons pointing the joints in the granite blocks. Two tiers of caisson—total height, 20 ft.—were generally held sufficient to keep out the water; but in places where rough seas and much spray were likely to occur, a third tier, or at any rate a portion of it, was put on. The south-east caisson on Inchgarvie had a special temporary caisson constructed for it, consisting of plates 22 ft. in length. (See Figs. 36 and 53.)

The four Queensferry caissons, after being launched, were at once towed out and placed in their proper positions, being secured to the jetty in such a manner as to allow their rising and falling freely with the tide. The Inchgarvie caissons, on the contrary, were merely placed in a temporary berth near the end of the jetty, and they were completed there, and had the temporary caissons put on and all necessary machinery placed inside, before they were removed to their permanent places. This was done, not only because it was essential that these caissons should touch ground as soon as possible after their arrival in their berths, but also because a large proportion of the machinery inside and of the temporary caissons, was taken from the Queensferry piers, then already built up to above high water, and put on board, and the transport and double handling thus saved. It may not be amiss to state, as an instance, that the last caisson—No. 6, or south-west Inchgarvie—was launched on May 29, 1885, weighing a little over 500 tons, with a draught of 10 ft. 3 in., was towed to Inchgarvie on July 16, drawing 31 ft. of water, and weighing 2877 tons, which was made up as follows:

	Tons.
Permanent caisson...	457
Temporary caisson (two tiers)	65
Two air-locks, air-shafts, concrete mixer, boiler, steam crane, &c.	35
Timber floors and staging...	50
Concrete	1418
Brickwork	852
Total	2877

Before entering upon the description of the mode of sinking the caissons, some account is needed to be given of the apparatus and machinery in connection with that part of the work.

Air Compressors.

There was nothing in these different from any ordinary type of compressors. They consisted of a pair of horizontal engines coupled, and directly acting upon a pair of double-acting air-compressing cylinders. There were two pairs of 16½-in. cylinders with 2-ft. stroke, and three pairs of 12-in. cylinders with 2-ft. stroke, all working at 60 lb. steam pressure. They were run up to any speed required to produce the necessary maximum pressure, which in the case of Inchgarvie on one occasion amounted to 37 lb. per square inch in the air-chamber of the south-west caisson. The air-compressing cylinders were water-jacketted, with a continuous current of cold water passing through. For the service of the rock drills inside the working chamber, a separate engine was used, which forced air down by a separate pipe lead at 70 lb. per square inch—the rock drills receiving, of course, the benefit of the difference between that pressure and the prevailing one in the air-chamber only, as they had to discharge into the general pressure of the working chamber.

On the top of the men's air-lock a whistle was set which worked by air pressure and which could be regulated from below; by means of this a constant communication was kept up, and more or less air pressure put on in accordance with requirements.

The pipes supplying the air were laid from the compressors straight to the caisson side, but the joint to the pipes inside the caissons had to be made by a long piece of flexible tube, the end of which was attached to a check valve placed upon the air-lock for the admission of the men. The air was forced down this shaft into the working chamber, thus preventing the ascent of any foul air in these parts.

A supply of water for flushing purposes was also laid on, being taken from an overhead tank set about 40 ft. above the level of the staging.

Of great importance both for the safety and convenience of the men, and for the progress of the work, were the air-locks. Those by which access was got to, and exit from, the air-chamber, consisted of an inner portion, 3 ft. 6 in. in diameter, in continuation of the ascending shaft, and a circular space all round it about 21 in. wide and 6 ft. high. (See Figs. 38 and 39.) The outer chamber was divided by two partitions into two equal spaces. Each of these spaces was provided with a square door giving communication on the one side to the air-shaft, and on the other side to the outer atmosphere. All doors opened to the inside. To gain admission to the air-chamber it was necessary to enter one of the outer spaces, to close the door (which was pressed against an india-rubber joint), and by turning a small cock to gradually admit compressed air. As soon as the pressure on both sides of the door leading into the air-shaft was equal, this latter fell open and the air-chamber could be reached by an iron ladder fixed in the shaft. To return from the air-chamber to the outside was the reverse of this, the pressure from the outer chamber being exhausted by opening a small cock communicating with the atmosphere.

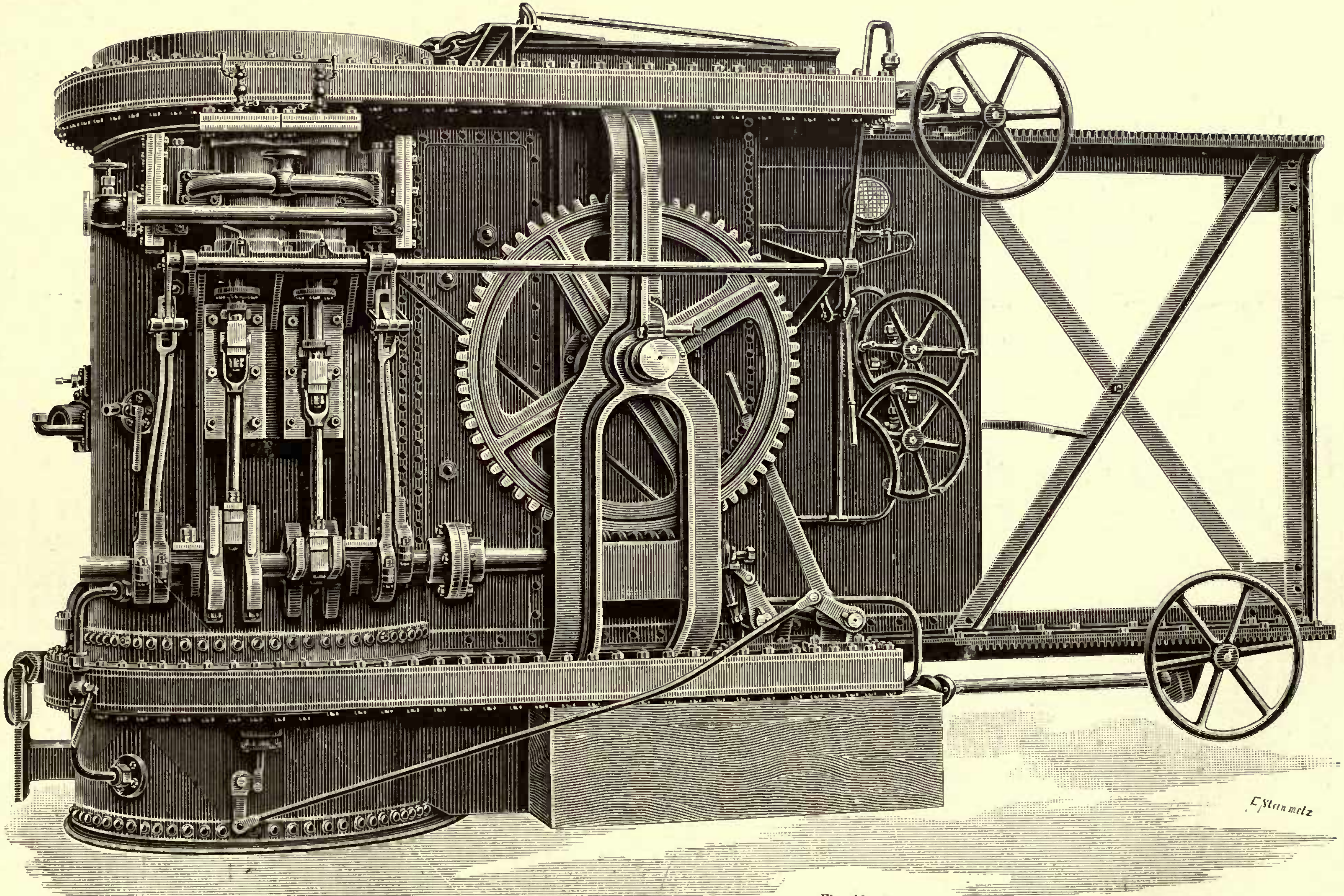


Fig. 40.

The cocks admitting pressure from within, or allowing the same to escape, were made of small bore, to prevent any one from making this change too quickly, as this would not be unaccompanied by risk of injury to the person exposed to it. One man was seriously injured by the india-rubber joint of one door suddenly giving way and exhausting the pressure in an instant of time, instead of taking from one and half to two minutes. Fortunately, the subject was a strong and healthy person, and well accustomed to high-pressure work, otherwise the result might have been fatal. As it was, there was considerable bleeding from the nose, the mouth, and the ears, and some pains in the limbs.

The lock for admitting or removing material was different in construction. (See Figs. 40, 41, 42, 43, 44, 45.) The principal portion of it was also a part of the 3 ft. 6 in. air-shaft closed at top and bottom by a sliding door. A recess was left at each end for these doors to enter into when drawn open, and there was a further recess which contained the winding drum for lifting and lowering the buckets. The sliding doors were worked by horizontal hydraulic rams, but could, in the absence of water pressure, be moved by rack and pinion and handwheel. By an interlocking arrangement of simple construction it was impossible to open both doors at once, a contingency which would have been fatal to the men working in the air-chamber below. The winding drum was driven by a worm and wormwheel outside the lock, and actuated by a pair of ordinary reversible engines, the main shaft which carried the drum being provided with air-tight glands at both ends where passing the sides of the air-lock. A chain passed round the drum and over a snatchblock suspended

AIR-LOCK AND HOISTING GEAR FOR CAISSONS.

Fig. 41.

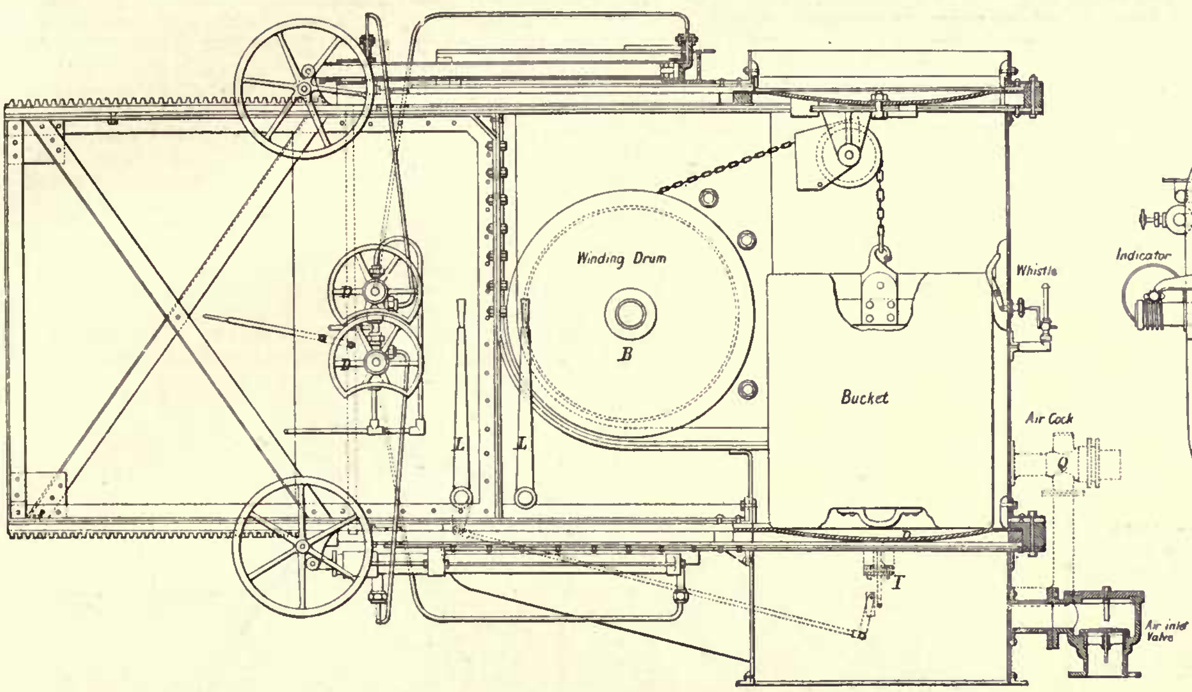


Fig. 44.

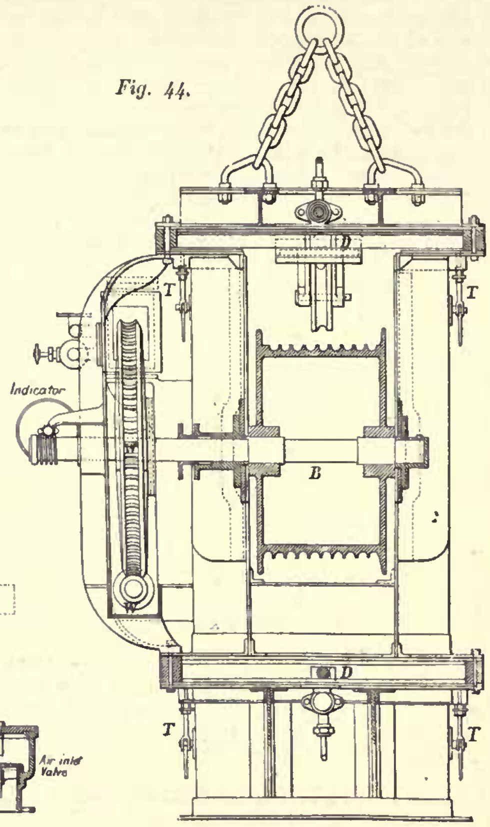


Fig. 42.

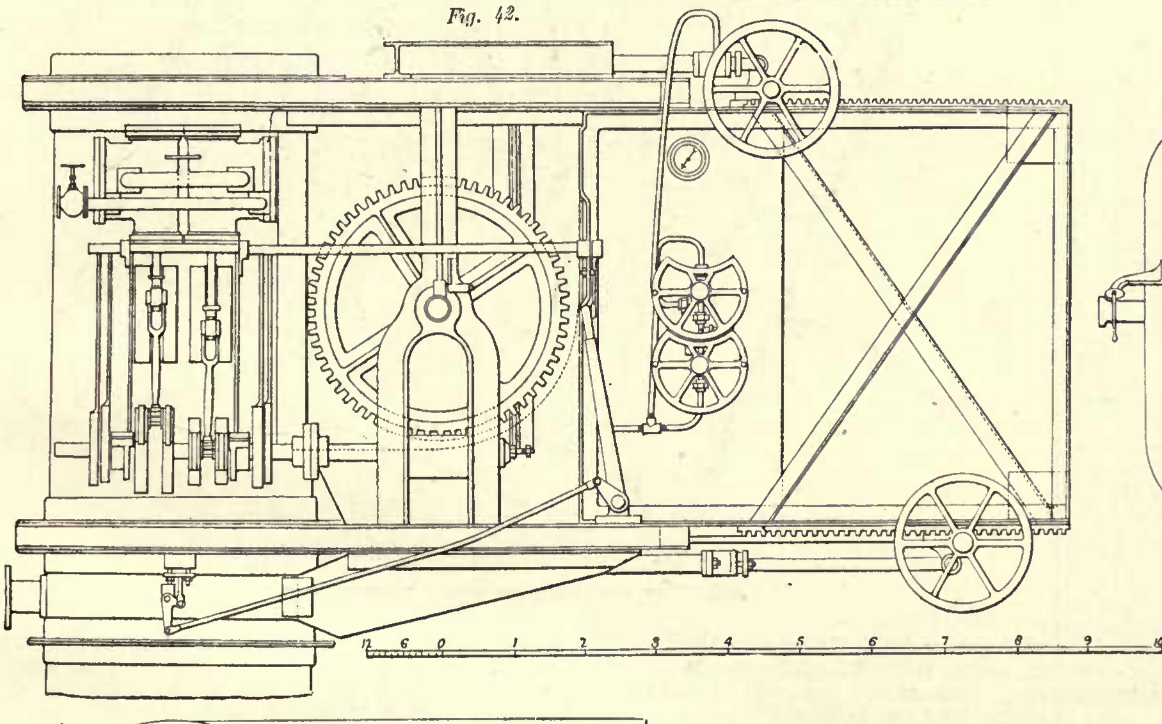


Fig. 45.

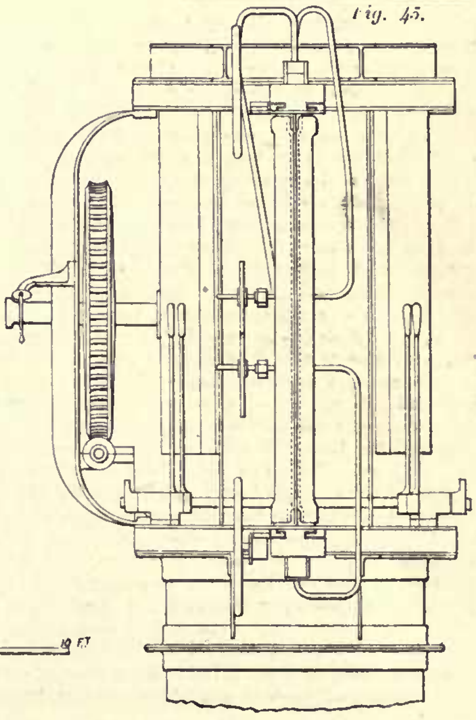
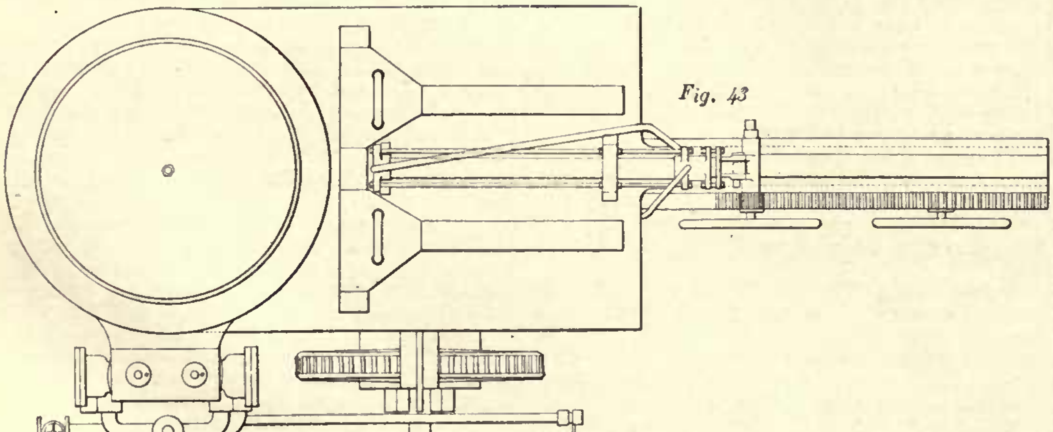


Fig. 43



to the under side of the upper door and sliding out and in with it, thus bringing the point of suspension immediately into the centre of the shaft.

The mode of working these locks was as follows: A 3-ton steam crane with fixed jib (see Figs. 36 and 51), but provided with quick-moving slewing gear, was set up near the lock so as to centre the air-shaft with its heaving chain; the top door of the lock was then drawn back and the skip or bucket, about 3 ft. in diameter and 4 ft. high, holding about 1 cubic yard, was lowered down into the lock and the shackle of the inside winding chain attached to it. The upper door was now closed, and a slight turn of the engines tightened the chain and lifted the bucket just clear of the lower door. A cock, or valve, which communicated with the compressed air in the working chamber, was now opened and pressure thus admitted to the lock. The sliding doors were provided with india-rubber joints, and small thumbs or tappets, actuated by a lever, were used to force the door hard up against the india-rubber, in addition to which the gradually increasing air pressure helped to close the joint. When the upper door was thus secured, a turn of the interlocking wheels set the lower door free; this was now drawn back, and the bucket was lowered right down to the bottom of the working chamber, and there filled with the spoil of the excavation, or else the chain was taken off and attached to one already

filled. A signal was then given, the bucket was drawn up into the empty lock, the lower door closed, the compressed air let out of the lock, the upper door drawn back, the winding chain taken off, and crane chain attached, the bucket drawn up and discharged on a shoot over the side of the caisson, and the same process repeated as before described. In the drawing shown (Fig. 41) it will be noticed that the bucket in its ascent in the lock touched a lever, and gave indication of its whereabouts by a steam whistle; but, as an additional precaution, small wheel gear was placed in connection with the winding drum-shaft, and, by means of a dial and pointer, indicated the position of the bucket at all points of its course.

The lever K acted upon the long rod L, which was so arranged that one of its ends was always within a hole drilled in the frames of the sliding doors, and that thereby either one door or the other was made absolutely immovable.

The two valves admitting water to the rams working the sliding doors are seen at D D close together; each carried a handwheel, out of which a segment is cut, and into this the rim of the other wheel fitted. In the position here shown the upper valve is closed, and its handwheel cannot be turned unless the handwheel of the lower is turned round to bring the cut-out segment exactly opposite. In that position, however, the lower valve would be closed, and it is, therefore, easy to perceive that, so long as the handwheels remained attached to the valves, it was impossible to open both simultaneously.

Since no workmen passed through these locks, it was not necessary to admit or discharge the air pressure by degrees; the inlet and outlet cocks were, therefore, large, and acted expeditiously to reduce the loss of time.

Accident to No. 4, or Queensferry North-West Caisson.

This caisson was built and launched in the usual way and towed into position at the north-west corner of the Queensferry jetty in December, 1885. It was secured to the staging in the usual way, allowing it to rise and fall with the tide pending the putting on and rivetting of the remaining courses of plates at top, and the otherwise completing it for the sinking process. Owing to the inconsiderable depth of water, the cutting edge touched the mud soon after half ebb, and embedded itself at low water. On New Year's Day, 1884, an exceptionally high tide occurred, followed by an equally exceptional low ebb, and the caisson sank deeply into the mud, assuming, no doubt, somewhat of a list or dip in accordance with the natural slope of the mud. The cutting edge entered so deeply into the more solid portion of the mud or silt that, on the flood tide returning, the water could not get underneath, and the caisson failed to rise with the tide. Not being built high enough, the water soon flowed in, and filled it completely; and on ebbing, as the lower sluice valves could not be got at, the caisson became top-heavy, and tilted still more over towards the low side. At last, it began to slide in the same direction, and moved thus for about 20 ft., when it stopped. In this position the lowest portion of the top plates remained fully 6 ft. under low water, and it became necessary to arrange to add to its height before pumping could be resorted to. A number of divers were employed to bolt on two or three tiers of plates.

Arrangements were made to stiffen the caisson internally by timber struts on top, and to keep on stiffening in the same manner as the pumps succeeded in reducing the water level inside the caisson. Unfortunately, the pumping was carried on at too great a rate for the carpenters who were to put in the strutting, and the thin plating could not support the pressure of the water from outside. The plates gave way, and a great rent, right across the lower side of the caisson, some 25 ft. to 30 ft. long, was the result. After discussing many plans suggested for getting out of this difficulty, it was resolved to construct a sheath or barrel of 12-in. timber balks all round the caisson, to bolt as many of these balks as could be got at firmly through the iron skin, and to make the best joint that could be got either by puddle clay or cement grouting, or a combination of both. All this work below had to be done by divers, and therefore required a considerable time in doing. In the first instance, a heavy circular timber frame was placed inside the caisson near the top and strutted in all directions. A number of balks were first placed all round, and, where necessary, driven down into the soil as far as required. Strong iron hoops or belts were laid round all these. and then the filling between these guide timbers carried on, all of them being V grooved on the one side, and the other side V shaped to fit the groove. Finally, wedge piles or closing piles were driven in between the other balks, and as many as could be got at were bolted tight up to the skin of the caisson where it was sound. Nearly ten months had elapsed since the accident occurred before the timber barrel was in such a condition that pumping out could be proceeded with (see Fig. 46). The ground under the high side was now dredged away, and both air and water were forced down the air-shafts into the chamber to wash or force out as much as possible from underneath. Pumping was then commenced, all leaks as they showed being dealt with in any suitable manner, further stiffening inside resorted to where necessary, and thus, step by step, the lost ground fought for. Weight was also added on the high side by commencing to build a brick casing against the outer shell. Patiently this work was persevered with, and at last, one Sunday morning, October 19, 1885, somewhat unexpectedly, the caisson raised itself out of its muddy bed and floated once more. It was at once drawn into position, and no time was lost in commencing the sinking process. As it was impossible to place a new shell in the place where it was rent, it was decided to leave this alone, and not to proceed with the building of the inner shell either, but to substitute for both a stout lining of clinker bricks built in cement. The shape of this and its strength are shown in Fig. 47.

The three other Queensferry and the two south Inchgarvie caissons had in the mean time been sunk to their full depth, and in fact had nearly disappeared out of sight, and all machinery and apparatus were available for dealing with this the last.

Before the middle of February, 1886, this prodigal among caissons had joined his brethren far down in the prehistoric clay, and there is no reason to think that the masonary pile which stands on it is less able to carry its due share of the enormous load laid on them than either of the others.

The foundations of the four circular piers on Fife, and of the two circular north piers on Inchgarvie, have been fully dealt with, and it remains to describe the mode of founding the two south piers on Inchgarvie and the four piers at Queensferry. The two former are founded on the solid rock, sloping here at an angle of about one in five to the south-west; while the four piers at Queensferry are placed on the boulder clay which is found there in a very hard and solid state at a minimum depth of 48 ft. below high water. The boulder clay here is sloping to north-north-east, also about one in five. These caissons were all sunk by means of the pneumatic process at considerable depth under water, under some difficulty, and under great pressure of air. To manipulate these cylinders of immense size, weight, and height, in the face of the uncertain conditions of wind and weather, and under the influence of a strong tidal current; to put them—weighing between 3000 and 4000 tons—into their places, and to hold them there and pass them down through material ranging from soft mud to hard rock, was certainly a most formidable task. Yet, with one exception, just above mentioned, namely, the tilting of the Queensferry north-west caisson, these huge cylinders caused proportionately less trouble and anxiety than the shallow cofferdams of the other foundations. This was, no doubt, owing in a great measure to the practical knowledge and experience of the men in charge of this portion of the work. The sinking of these six caissons was let as a sub-contract to M. Coiseau, of Paris and Antwerp, whose large staff of men had been engaged for several years in the construction of the great quays and harbour walls and docks at the latter place by the pneumatic process. It would be as well to take this opportunity of dispelling the notion which has somehow gained credence, that the foreign workmen—mostly North Italians, with a sprinkling of French, Belgians, Austrians, and Germans—were better able to work in and resist the high atmospheric pressures necessary to this kind of work, than the British workmen. That this is not so is proved by the fact that large numbers of the Forth Bridge men—carpenters, fitters, and ordinary labourers—were frequently employed below, and many of their number for the first time, when the pressure was already considerable, without experiencing any great inconvenience or harm. It is, in the first instance, a matter of habit, although it certainly requires good health, freedom from pulmonary or gastric weakness, and abstemiousness, or, any rate, moderation in taking strong spirituous liquors. Some of the most experienced hands of M.

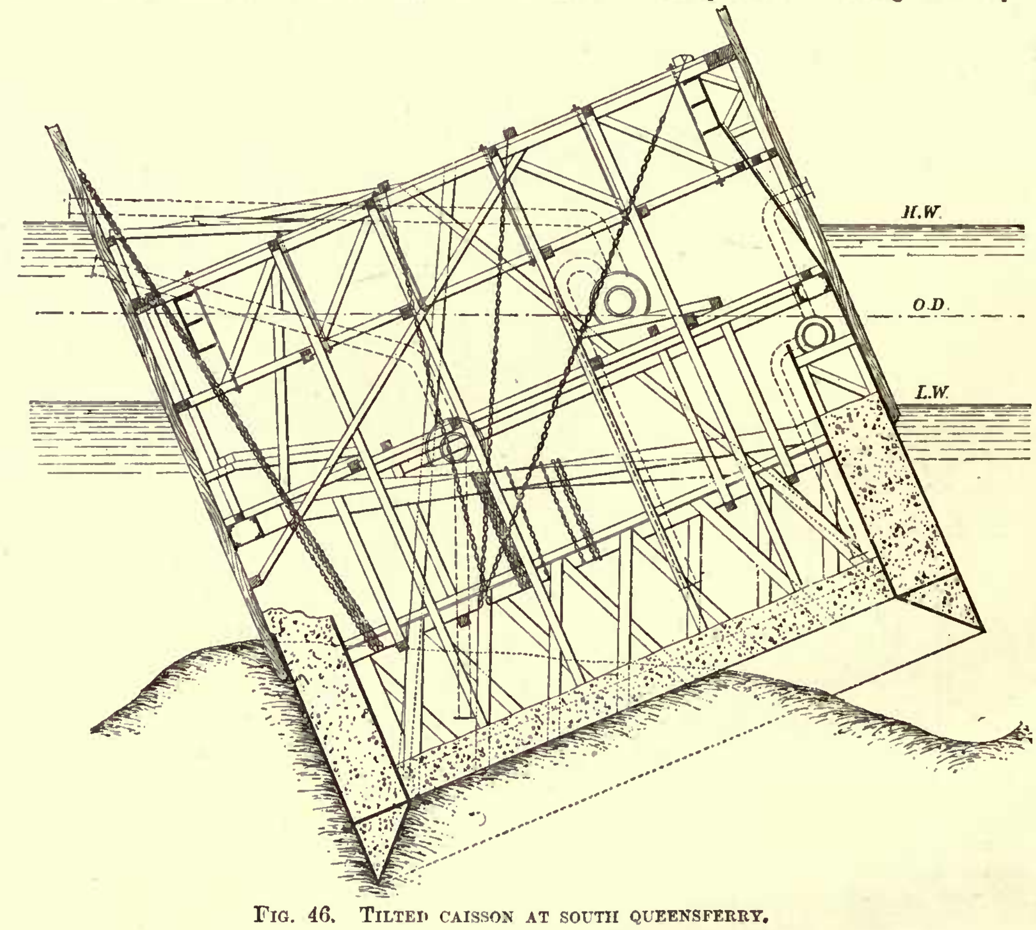


Fig. 46. Tilted caisson at south Queensferry.

Coiseau suffered when they had been making too free with the whisky overnight, and a good deal of the disorders that ensued were traceable to the same source; though, on the other hand, wet feet, or incautious and sudden change from a heated atmosphere into a cold and biting east wind, insufficiency of clothing, and want of proper nourishment, had their influence in causing illness among the workers. Although these six caissons were founded at depths varying from 63 ft. to 89 ft. below high water, with an average time of seventy-eight days for each, not one death can be properly and justly attributed to working in high pressure. Two men died during the time, but both were already consumptive when they commenced working here, and the rigour of a Scotch winter had, at any rate, as much to do with their death as the air pressure. Another man became insane, and had to be sent back to his own country.

The principal bad effect produced by the air pressure appears to be that of severe pains in the joints and muscles of the arms and legs. As these have been, in most cases, traced to hard work and consequent copious perspiration, and also to too long a stay under pressure, it has been suggested as a probable cause that small globules of air make their way through the skin, or between the skins, where they remain, and on the workman returning to ordinary atmospheric pressure, expand, and thereby cause the most agonising pains in the joints, the elbows, shoulders, knee-caps, and other places. In seeming confirmation of this, the sufferers got instant relief on returning into the high pressure. Thus it happened that many of those afflicted with this disorder spent the greater part of Saturday afternoon and Sunday under air pressure, and only came out when absolutely obliged to do so. Various researches were made by members of the medical staff in the endeavour to give relief or obtain a cure, but, so far, not with any degree of success.

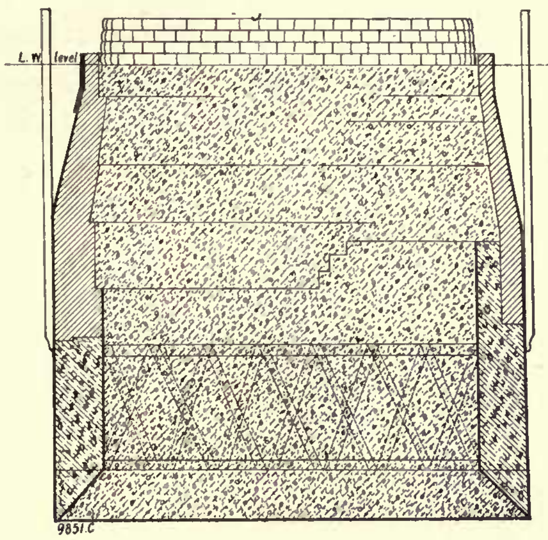


Fig. 47. Section of tilted caisson after completion.

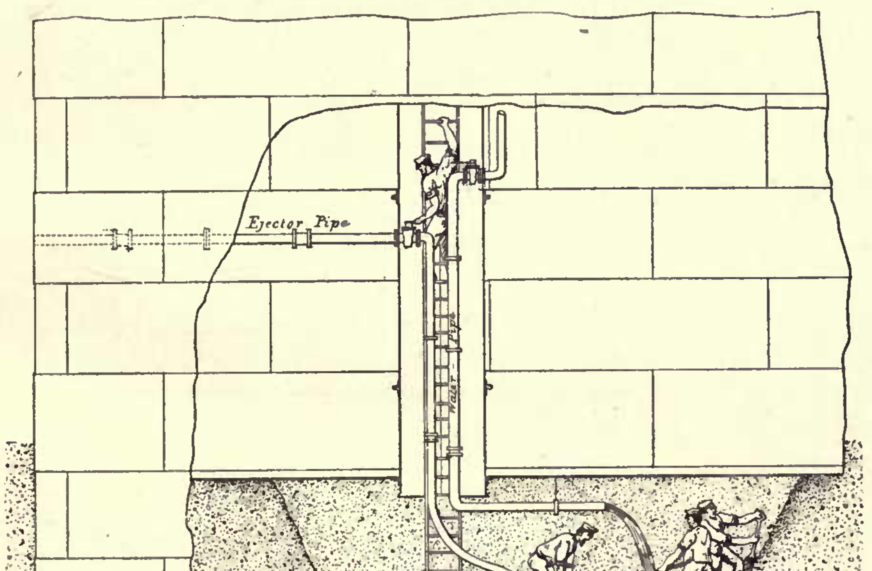
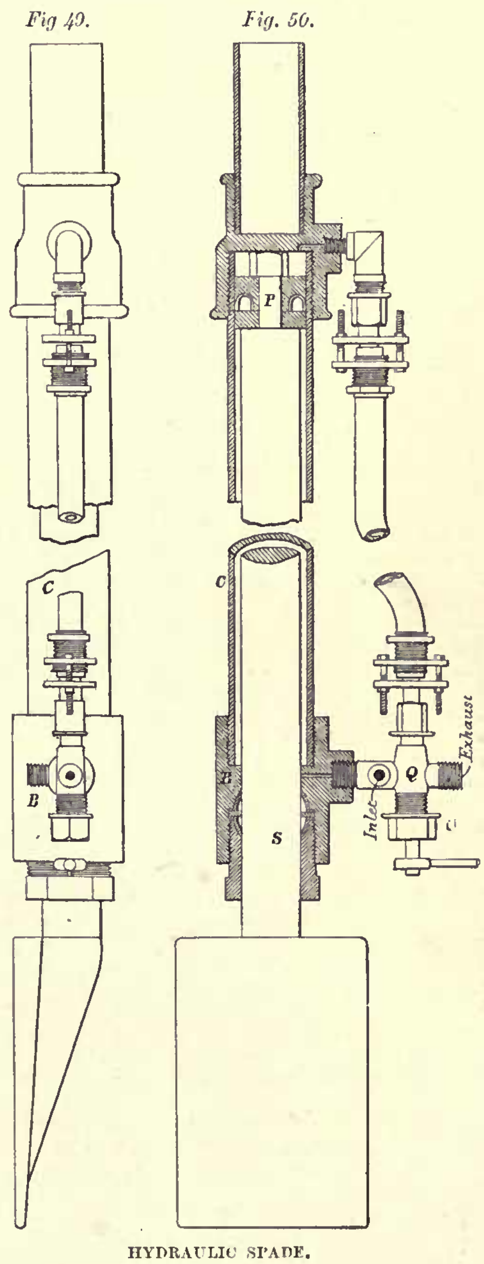


Fig. 48. Sinking the Queensferry caissons.



Hydraulic spade.

Sinking of the Caissons.

The operation of sinking a caisson through mud, silt, or clay differs somewhat from that pursued in sinking through solid rock, at any rate in the mode of attack.

In the Queensferry caissons the first thing to be done was to fix pipes in the air-shaft, one for the admission of water, the other for the removal of mud diluted with water. As this process of ejecting matter will be described further on, it need only be mentioned that by degrees the shaft first, and next a space underneath it in the air-chamber, was cleared, and access had to the latter. As soon as the ejector pipes described above could be reached, flexible hose was attached to them, and a larger number of men employed to clear the caisson of the semi-fluid mud. Great care was required during this early stage of the work, and the weight of the caisson regulated to a nicety, for there was nothing but its buoyancy to prevent it from suddenly descending and smothering the men below. At low water was naturally the most dangerous time, there being the least displacement in action then, while the weight was greatest, and moreover the cutting edge resting upon a treacherous ground. The men were generally withdrawn at this time, and the air pressure diminished, allowing the caisson to descend as far as it would go. On one of these occasions the caisson suddenly descended some 7 ft., and not only the air-chamber but part of the ascending shaft became filled again with mud and silt. It is satisfactory to be able to say that not a single life was lost here from this cause, which in other works had proved fatal to so many.

In using the ejectors the following mode of working was employed. (See Fig. 48.) A sort of sump or hollow in the ground was formed, and into this the water from an overhead tank was allowed to flow in any quantity desired, and mixed with the more solid material excavated. A man who held the end of the flexible hose attached to the ejector manipulated the same in such a manner that a certain amount of the air inside the chamber was allowed to enter into the ejector pipe with the mixture in the sump. This air in escaping carried with it a certain amount of liquid, and forced it out at one of the openings in the caissons above water level. The operation is shown in the cut figured here. It is somewhat puzzling at first to understand why the air pressure, which is only just equal, or only slightly exceeding that which is due to the head of water outside, should lift and discharge a quantity of semi-solid material at a level above the water; the explanation will, however, be found in the fact that the velocity of the air due to this pressure is very much higher than that of water flowing under the same head, and that it carried mechanically along with it as much of the fluid as it could convey. Of course the man who manipulated the end of the hose in the sump had to feel his way into the solution of this problem, and had to vary the quantities or proportions of air and liquid according to the requirements of the moment. Outside the caisson the flow from this ejector was not continuous, but in gulps, like that from a single plunger pump, now in a large mass, now in a thin stream, and at times nothing at all.

As soon as all the soft material had been removed, and a bed of stiffer clay reached, the ejector

could be used only for removing the superfluous water, and picks and heavy spades had to be resorted to and the material charged into the buckets and hoisted out by the locks. Lines of narrow-gauge railway were laid down to run small bogies, on which the skips were carried in all directions within the chamber. Presently the hard boulder clay was reached, which was nearly dry, and which proved tougher and harder than anything the existing tools could work in. Various means were tried, and even blasting by powder or dynamite resorted to, but with little result. The rate of progress became exceedingly slow, and the men's energies became quite exhausted. Here Mr. Arrol's ingenuity fortunately came to the rescue, and he devised a most simple, yet a most efficient, tool to grapple with this difficulty—namely, a hydraulic spade shown in Figs. 49 and 50. It consisted in the main of a ram, to which a spade is attached, the ram fitting into a cylinder, which represents the handle of the spade. On the top of the cylinder was fitted a head-piece, which could be set against a piece of batten or any other convenient object. The ceiling of the air-chamber furnished the resistance, and the projecting rivet heads were useful in preventing side slip of the head-piece. The spade was lifted by two men, a third attending to the fixing of the head and the turning of the cock admitting water pressure. This was of the ordinary amount, namely, 1000 lb. per square inch, less the amount of air pressure inside the caisson.

The spade was set on the ground, the pressure turned on, and as soon as the head-piece had been firmly set against the ceiling the full pressure was given, and the spade forced down into the clay. The water was then exhausted and the spade brought forward, thereby detaching a slab of clay from 16 in. to 18 in. deep, and from 2 in. to 4 in. thick. The spade was then set up again, and the clay thus cut away in long ridges all over the area. Many of these slabs of clay had to be cut to allow them to be charged into the skips. Any boulders too large to pass through the air-shaft were either drilled and blasted, or left in the chamber to be hereafter incorporated with the concrete filling. The water discharged by the spades had to be collected in a sump and discharged through an ejector.

In digging or undercutting the edge of the caisson all round, the spades had to be worked at an angle varying from 30 deg. to 60 deg., the rivet-heads coming in usefully here to provide a good hold for the headpiece of the spade.

In undercutting round the sides, portions were left standing to carry the weight of the caisson while excavation was still going on, and these portions were by degrees removed until the bearing surface became too small to sustain the weight, and the caisson settled down into them. In proportion as the caisson descended, more weight was added on the top; but this was also required to be done with care, for fear of displacements taking place. After entering into the hard clay, the caisson edge was nearly sealed by the pressure of the water upon the clay outside, and instead of the pressure of air corresponding to the head of water outside, a few pounds sufficed to keep the caisson dry.

Thus, in the case of the Queensferry north-east caisson, founded at 89 ft. below high water, the outside head is equal to fully 42 lb. of air pressure inside, but it was actually worked and finished with a pressure of from 15 lb. to 18 lb. per square inch, after once the hard clay had been entered. This made it, of course, much easier for the men to work in, apart from a considerable saving of wear and tear of the machinery.

It will be readily understood that it was of paramount importance that the caissons, when sunk to their final depth, should be in the correct positions laid down for them; yet it is equally easy to understand that in sinking such a mass it would not take a great deal to cause a displacement in one way or other, since there is nothing to hold it in its proper centre.

The position of each caisson was therefore checked nearly every day, and if it deviated in any way from its right course, steps were at once taken to remedy this. To do this it was only necessary to undercut the caisson edge on the side to which it had moved, and to gradually tilt it to a small degree in the direction of that side. When this had been done the caisson was sunk further down for a distance with this tilt on it, and was then righted by undercutting on the high side. This was repeated until the centre of the caisson had got back to its proper position. The slight upward taper in the cylindrical portion of the caisson added some little help in that direction, and the writer thinks that a little more taper than that given to the Forth Bridge caissons would be found very advantageous in future works of this kind. Another plan is to set up inside the air-chamber and against the top of the sloping plates of the shoe, a number of strong timber struts at an angle to the perpendicular, and well secured against some timber or stone in the solid ground. This should be done previous to the caisson being allowed to descend. When it does so all these struts have a tendency in descending to become longer and to force thereby the caisson over in the direction in which it is intended that it should go. This should also be done at high tide, when the buoyancy of the caisson is largest. As in all things, so here, prevention is better than cure, and it is best to keep a sharp eye upon the workmen in the chamber, to insist that the edge be undercut on the outside to the extent of 6 in. to 8 in. all round before it is allowed to descend, and to have the position checked as frequently as possible, in order to find out a movement to any side at once, and not allow it to become too great to be remedied. In working on a sloping face, whether of rock, silt, or clay, it is good practice to keep the caisson tilted very slightly to the lower side, which has the effect of forc-

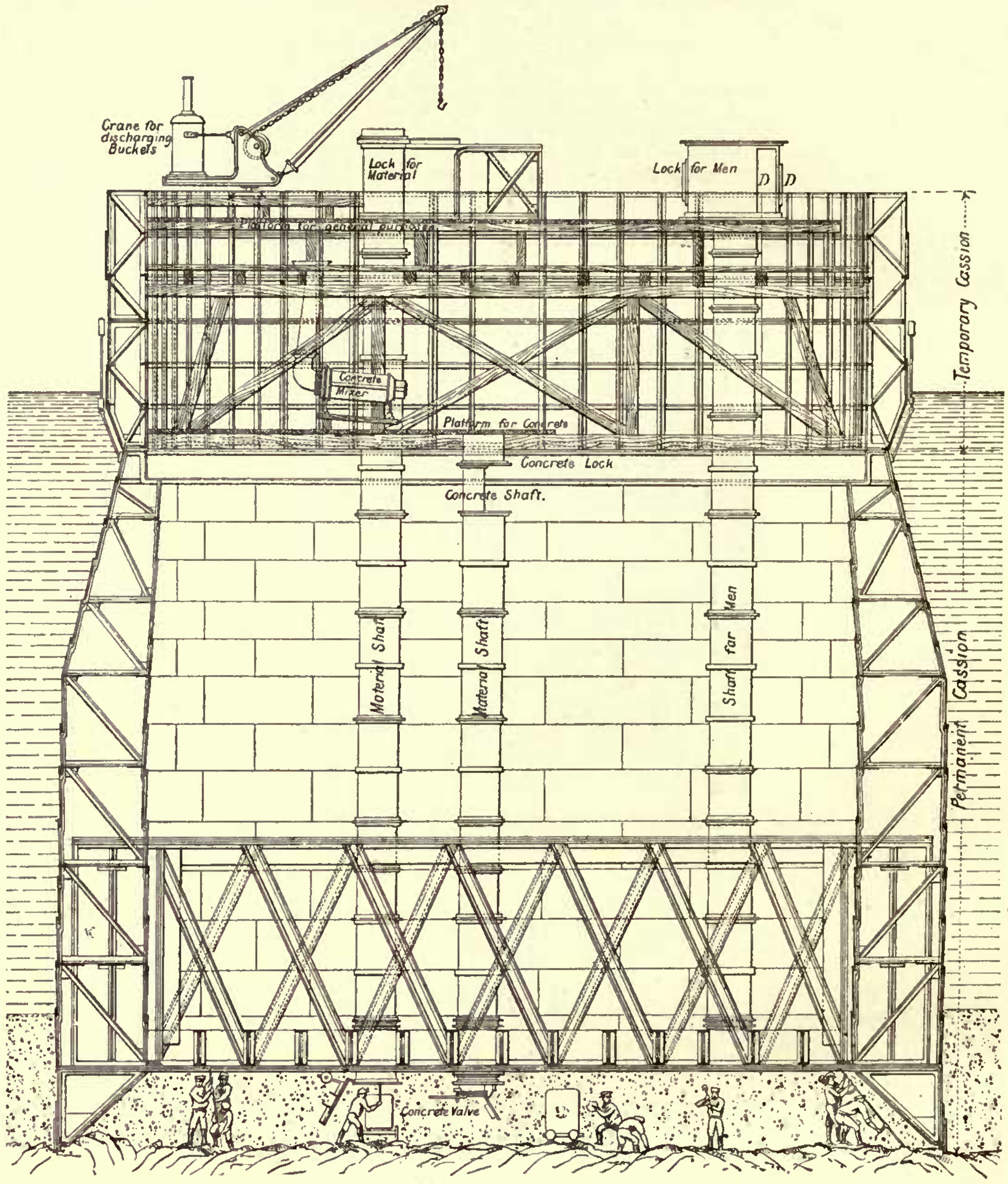
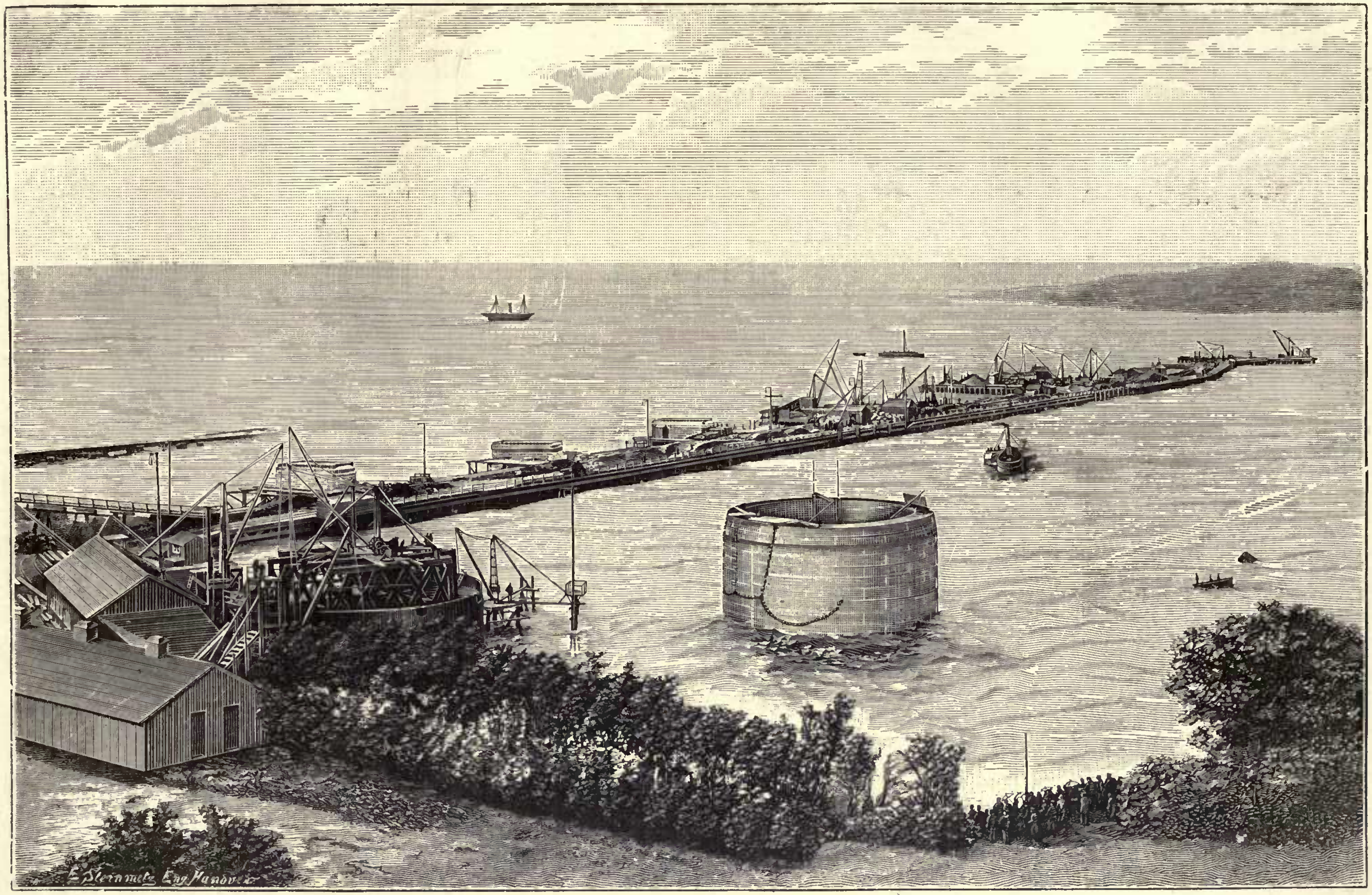


Fig. 51. Section of caissons with air-locks and working chamber.

TABLE No. V.—Progress of Work with Queensferry Caissons and Piers.

—	South-West.	South-East.	North-East.	North-West.
Launched and towed to berth ...	May 26, 1884	Aug. 24, 1884	Nov. 24, 1884	Dec. 3, 1884. Submerged Jan. 1, 1885. Floated again Oct. 19, 1885
Commenced sinking	Sept. 1, 1884	Nov. 24, 1884	Jan. 28, 1885	Nov. 25, 1885
Level of cutting edge at commencement below high water .	33 ft.	33 ft.	37 ft.	52 ft.
In final position	Dec. 6, 1884	Feb. 4, 1885	April 10, 1885	Feb. 4, 1886
Level of cutting edge below high water	71 ft.	73 ft.	89 ft.	85 ft.
Commenced concreting of air chamber	Dec. 8, 1884	Feb. 7, 1885	April 14, 1885	Feb. 5, 1886
Finished concreting of air chamber	Dec. 17, 1884	Feb. 18, 1885	April 25, 1885	Feb. 10, 1886
Concrete up to granite level ...	Feb., 1885	April, 1885	June, 1885	March, 1886
Pier completed	July, 1885	Sept., 1885	Sept., 1885	June, 1886

FLOATING OUT CAISSON FOR QUEENSFERRY PIER, MARCH 26, 1884.



ing it up, but this should not amount to more than the natural batter of the outside shell. A few inches one way or the other is of no consequence in so large a caisson, as the pier raised upon it could easily be centred as much as that to either side, but it is just as easy and much better to keep it right from the first. During the sinking of No. 4 caisson, owing to an error by one of the surveying staff, the caisson got out of position to the extent of 10 in., but it was brought back to its true position in less than three days, though as much as that could not be done in every case.

The excavation and the rate of progress varied naturally with each caisson, and while for instance the first, sunk through a depth of 38 ft. of material, took ninety-six days to finish, the last was done in sixty-nine days, through over 30 ft. of nearly all stiff material. Table No. V., on the preceding page, gives principal dates and figures of interest in connection with these four Queensferry caissons.

Queensferry Caissons.

The north-west caisson is the one which met with the accident we have described. Hence the time elapsed between launching and sinking. Table No. VI. shows the levels of strata below high water through which these caissons were passed during sinking. As all strata were more or less on the slope, the mean height is here indicated, except with regard to extreme depth of excavation, which is, of course, level. In the case of the north-west or tilted caisson, a considerable quantity of

mud and silt had been removed previous to its being raised; hence the greater depth at commencement of sinking.

When working in the hard boulder clay, for twenty-four hours with the full complement of twenty-seven men below in the air-chamber, and with four hydraulic spades going, a bucket was sent up every five minutes, or 288 buckets in the twenty-four hours, which was equal to a little over 5 cubic yards per man per twelve-hour shift. The total amount of excavation over the full area was equal to 145 cubic yards for each foot in depth. Even this rate of progress was frequently exceeded under favourable circumstances, but was of course largely above the average daily work.

TABLE No. VI.—Nature and Depth of Strata through which Caissons were Sunk.

All below High Water.	Level of mud or silt	27 ft.	$27\frac{1}{2}$ ft.	40 ft.	52 ft.
	,, clay and boulder clay	48 ft.	$52\frac{1}{2}$ ft.	75 ft.	62 ft.
	,, cutting edge at finish	71 ft.	73 ft.	89 ft.	85 ft.
	Depth through hard ground	23 ft.	$20\frac{1}{2}$ ft.	14 ft.	23 ft.
Total excavation in cubic yards		6372	6651	6827	6271

The different strata through which the caissons passed, were — water, deposited mud, stiff mud, silt, a layer of pebbles and stones, soft clay and boulder clay. In the last strata were found large rocks well rounded off, of granite, limestone, freestone and other kinds, many of which showed upon their flat faces, the distinct grooving or scoring due to glacier action. Amethysts and pebbles of all sorts, and large round boulders of conglomerate were also found, but no traces of fossils or of animal life, not even a live toad.

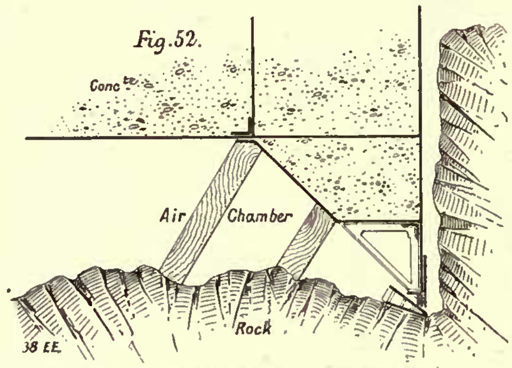
The excavation finished, the chamber was cleared of all material used during sinking, and preparations made for filling the whole space with concrete. The bottom ends of the air-shafts were closed by plates previously prepared, to which was attached a hinged door opening downwards. The large air locks were then removed from the tops of the shafts, and small tubes 18 in. in diameter fixed inside and carried up some distance to a platform, where the concrete mixer was stationed. A valve or small air-lock was set on the top of the 18 in. tube. Outside the latter was of course ordinary atmospheric pressure. Similar arrangements were made for the other small shafts placed in the caissons from the beginning. Concrete was now deposited close to the lock, a signal was given, and the lower door in the air-chamber was hermetically sealed, the air let out of the shaft and the upper valve opened. Concrete was shovelled in till the pipe was nearly filled, the door then closed, and a signal given. Those below then opened a small valve to let compressed air into the shaft, the lower hinged door was opened and the mass of concrete fell on the floor and was taken up into barrows and carried all round the edge. There it was firmly rammed in and pounded with wooden rammers into every hole and corner, and thus gradually laid up the sloping face of the shoe. Against the ceiling also the concrete was carefully rammed, and thus by degrees the whole chamber built in, leaving only passages between the places where the concrete was passed down. These also were by degrees filled up, and the last of the concrete had to be passed through the men's lock and down the air-shaft in buckets until this also had to be filled. The air pressure was of course kept on during all this time to keep the water from washing in and out. Finally, all the shafts were filled up, and cement grout was run into these until it stood up to the level of the water outside, the pressure being kept on these shafts for about thirty-six hours longer. The remaining space of the caisson above the air-chamber was now filled up with concrete to the low-water level at which the granite courses commenced.

The concrete in the air-chamber was of the following proportions: Round the cutting edge and under the shoe, and for about 4 ft. all round within this space, 27 cubic feet of stone, $6\frac{1}{4}$ cubic feet of cement, and $6\frac{1}{2}$ cubic feet of sand. Inside this space and inside the caisson above the air-chamber, the proportions were 27 cubic feet of stone to $4\frac{1}{2}$ cubic feet of cement, and $4\frac{1}{2}$ cubic feet of sand. The grout used was pure cement and water.

Inchgarvie Caissons.

With regard to the Inchgarvie south caissons, the mode of working varied somewhat owing to the nature of the rock bottom. The preparations which had been made for the reception of these caissons, and the levelling by means of concrete piers and sandbags, has already been described. Previous to launching the two Inchgarvie caissons, a strong timber shoe was fixed in each of the two places which would come to lie immediately upon the two piers (Figs. 30 and 31), built up of concrete bags on the opposite side to where the caisson was likely to first touch the rock. The timber frame was brought down flush with the cutting edge, so as to give the caisson a solid base to rest on.

When floated across from the Queensferry jetty the caissons were at once attached to the mooring chains provided for them, and, in addition, had stout wire ropes passed round them, the other ends of which were passed round the north piers already



Struts and wedges in air-chamber

built. Careful watch was kept day and night to guard against accidents, and further loading with concrete was at once proceeded with, while the remaining machinery, air-locks, &c., were placed inside, and the flexible tubes for the supply of compressed air and water, attached. As soon as the caisson commenced to touch ground at low water, the loading was suspended, and a descent made into the air-chamber to examine the points where the cutting edge was touching, and to put in any further support that might be considered advisable. In this way two piers of sandbags were built up to the ceiling as an additional safeguard against slipping, and these piers were near the centre of the caisson, but rather on the side of the concrete piers. Work was now commenced in short shifts, both before and after low water, in order to remove as much rock as possible under the cutting edge on the high side, as it was deemed advisable that at least one-fourth to one-fifth of the circumference should rest on the solid rock and in a sort of chase before the caisson was loaded to such an extent as to prevent its floating even at high water. It was thus fully a fortnight after the caisson was moored in its place before it was allowed to settle down, and to rise no more. Excavation then commenced in earnest, although the rate of progress was slow at first owing to the comparatively small area which could then be attacked. The mode of working was very simple. A number of holes were drilled at first by ordinary hand jumpers, one man holding the drill and two striking; later on, by the pneumatic rock drills driven by compressed air at 70 lb. to the square inch. The holes were drilled under, and some 12 in. beyond or outside the cutting edge, and when carried to their full depth were plugged and others proceeded with, until a sufficient number were done. They were then charged with explosive and the charges fired. In these caissons also, blocks of rock were left standing for the cutting edge to rest upon, while between them the rock was removed. The rock-drills were also worked within the area of the chamber so far as the bottom was uncovered by water, and where possible ordinary quarrying with crowbars and heavy hammers was carried on. At first the charges were fired by time-fuzes, but, as the number of holes increased, insulated wires were laid to the boreholes, the ends being gathered together and brought up into the air-shaft, where they were fired by an electric battery simultaneously. A wooden trap-door was provided to close the bottom of the air-shaft and prevent the fumes from passing upwards, all the men being withdrawn during that time. After the charges were fired the air compressors were worked at somewhat greater speed to increase the pressure, and the chamber was soon clear again. The firing was done as often as possible at the end of a shift to cause the least delay and loss of time. The firing of the blocks of rock upon which the caisson rested, was generally done at low water, the caisson crushing into the débris with irresistible force. A number of men then descended and cleared away the débris, which was sent up in the skips, passed through the lock, and discharged over the side as described in the case of the Queensferry piers. Another lot of men cleared away some of the sandbags and cut under the edge into the concrete piers, while the remainder, were at once set to to drill fresh holes where isolated points remained standing.

As mentioned in connection with the Queensferry caissons, careful examination was daily made, or even oftener, as to the position of the centre of the caisson, and if it had shifted it was at once tilted to one side and speedily brought back to its place.

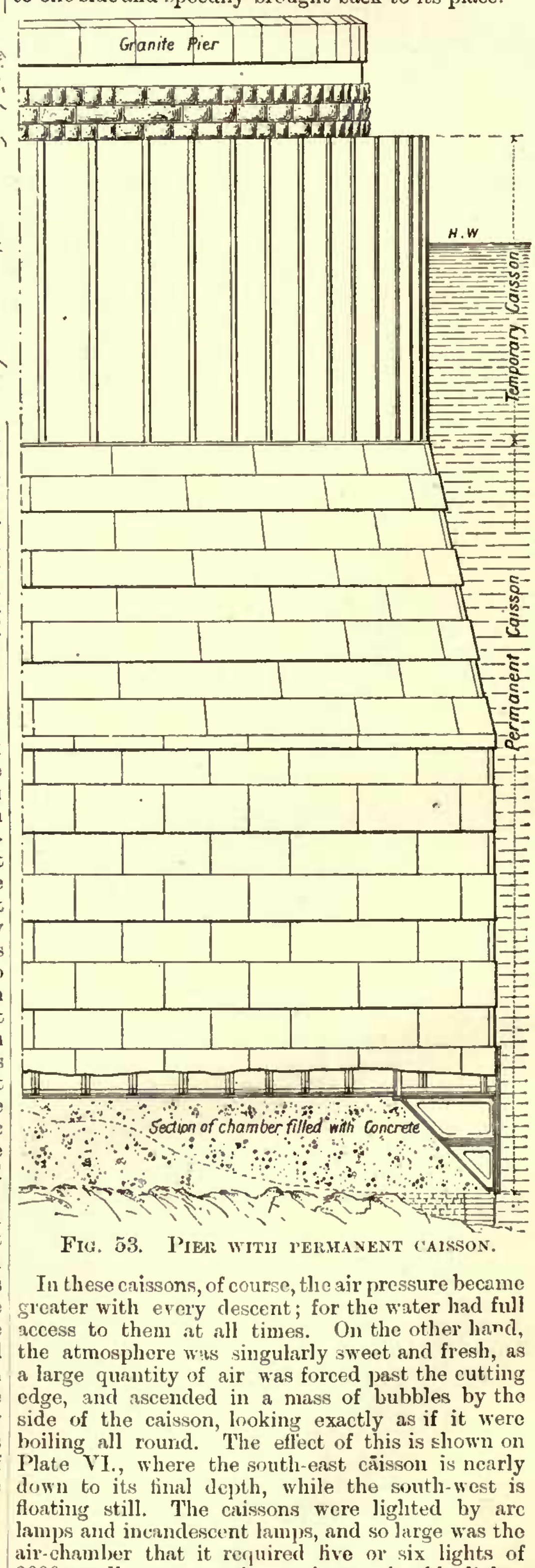


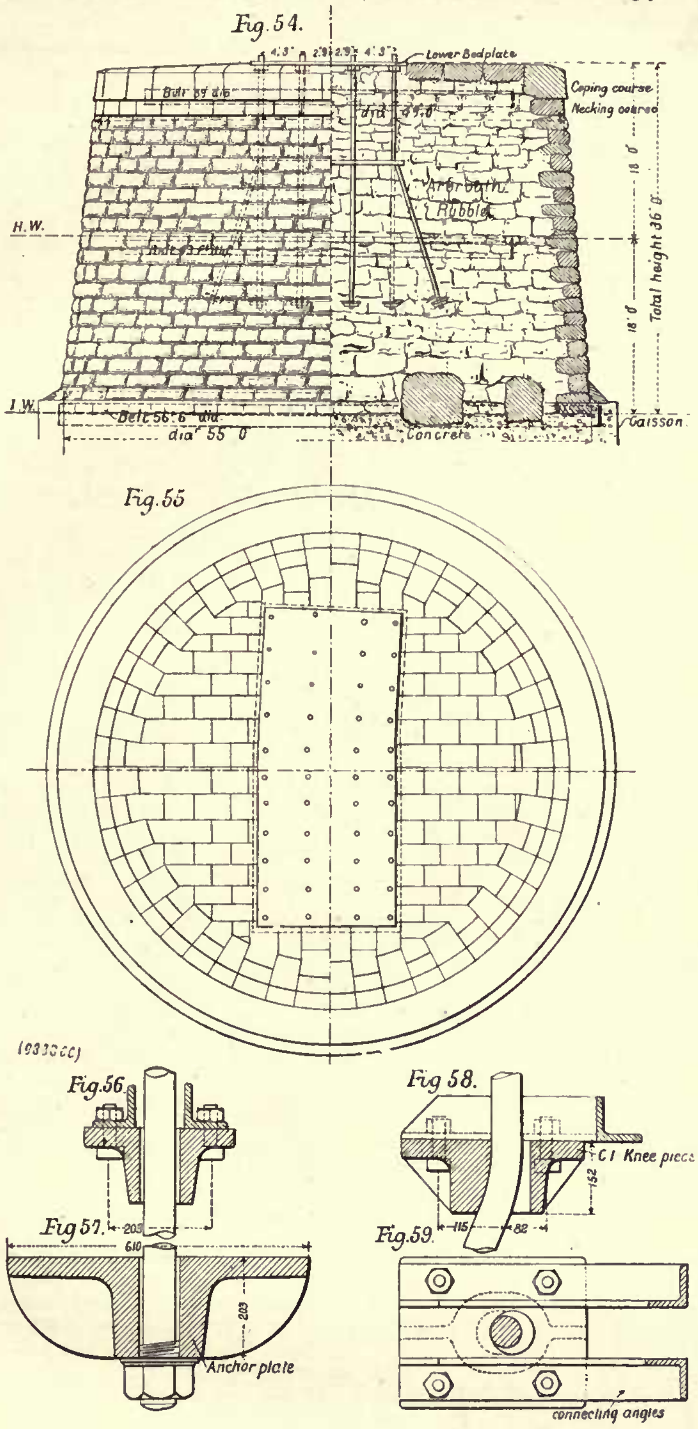
Fig. 53. Pier with permanent caisson.

In these caissons, of course, the air pressure became greater with every descent; for the water had full access to them at all times. On the other hand, the atmosphere was singularly sweet and fresh, as a large quantity of air was forced past the cutting edge, and ascended in a mass of bubbles by the side of the caisson, looking exactly as if it were boiling all round. The effect of this is shown on Plate VI., where the south-east caisson is nearly down to its final depth, while the south-west is floating still. The caissons were lighted by arc lamps and incandescent lamps, and so large was the air-chamber that it required five or six lights of 2000 candle-power each, to give a tolerable light; it took much care and trouble to protect the lamps and cables against the effects of blasting.

The rock-drills were of an ordinary type, mounted

on three-legged stools or stands for vertical or steep-inclined drilling, and on timber frames for horizontal or slightly-inclined working. The arrangement through which they were made to discharge the compressed air by which they were driven into the general atmosphere, did great service in keeping the air pure just in the places where most of the men congregated, and when in good working order, they drilled a large number of holes in the course of a day.

In these two caissons the tendency to go down hill manifested itself strongly, and powerful timber struts and hardwood wedges covered with steel plates had to be employed to keep the caisson in its position, or to force it back when it had moved. These were set on prepared faces on the rock, as shown in the sketch, Fig. 52, and their action upon the caisson will be readily understood.



MODE OF FIXING UNDER BEDPLATES ON PIERS.

TABLE No. VII.—Progress of Work on Inchgarvie Caissons.

	South East Caisson.	South-West Caisson.
Launched	March 30, 1885	May 29, 1885
Towed to its berth, Inchgarvie	May 15, 1885	July 16, 1885
Touched ground at low water	May 25, 1885	July 29, 1885
First descent to chamber	May 26, 1885	August 5, 1885
Commencement of sinking	May 27, 1885	August 6, 1885
Level below high water at commencement	51 ft.	64 ft.
In final position	August 15, 1885	October 1, 1885
Level of same below high water	63 ft. 9 in.	72 ft. 1 in.
Commenced concreting chamber	August 19, 1885	October 2, 1885
Finished concreting chamber...	September 1, 1885	October 10, 1885
Caisson filled to granite level...	September 15, 1885	October 30, 1885
First granite laid	September 19, 1885	October 30, 1885
Pier completed	November 20, 1885	February 22, 1886

The actual blasting of the rock under the cutting edge does not appear to have injured the steel edge in any way; but large chips of rock lodging between the outside face and the iron plating caused some indentations, which were not, however, of any consequence.

On several occasions photographs were taken in the air-chamber, some of them requiring an exposure of fifteen to twenty minutes; but they were not very successful, owing to the changes in the atmosphere and the uncertain light of the arc lamps. Whenever the air pressure increased to a slight extent the atmosphere became quite clear and transparent; then the air would rush out at some point under the caisson edge with a noise like distant thunder, and a great wave of cold water came rushing back. This caused a dense white fog to suddenly rise in the air-chamber, which obscured everything for a few moments and then gradually disappeared again.

Through the gaps left in the heaps of sandbags a number of strange visitors used to make their appearance, attracted, no doubt by the glare of the lighted chamber, which at night could be distinctly seen from above—such as salmon, dogfish, octopus, many other fish, crabs, and a large number of lobsters. One of the latter—a large specimen—got very excited in the chase after him, and leaped up nearly the full height of the chamber in his frantic endeavours to escape—finally jumping into an empty skip, whence he was promptly transferred to the boiling-pot.

With regard to the working hours of the men employed after the caisson had once settled down on the rock, work was carried on day and night, the only stoppage being from 6 P.M. on Saturday till midnight on Sunday; but the air compressors had to be kept going all the time, and the full pressure of air maintained. Watchmen were also kept constantly on duty in the chamber when work was not carried on. At first the men worked in eight-hour shifts, with eight hours off, later on six-hour shifts with six hours off, and finally, in the higher pressures, with four-hour shifts and eight hours off.

The total excavation for the four piers on Inchgarvie, and the four piers on Queensferry, and the four piers on Fife, are given in a tabular statement further down, together with other quantities.

The total of the wages paid by the sub-contractors to their employés, including managers', engineers', and time-keepers' salaries, amounted to 1*l*. 15s. per cubic yard of rock excavated in the Inchgarvie south-east caisson, and to 2*l*. per cubic yard in the Inchgarvie south-west pier.

Neither of the Inchgarvie caissons was carried down to the full depth contemplated (see Fig. 53), as it was found that only a very small area remained to be filled up when the caissons had got to the depth where they were left. These places were carefully levelled and stepped, and iron plates were fitted in to close the gap between the caisson edge and the rock, and the spaces were then carefully built up with concrete bags and the whole grouted with cement at slack water. Upon this foundation concreting was commenced, and the whole chamber gradually filled with concrete in the manner described for the Queensferry caissons.

In Table No. VII. are a few data of interest in connection with these two caissons.

The Circular Granite Piers.

The foundations below low-water level of ten out of the twelve circular piers, vary both in size and considerably in depth, but above that level they are exactly alike. The two exceptions are the two north piers on Fife already described. Their foundations start at 7 ft. below high water, and they are only 45 ft. in diameter under the necking course. In all other respects they do not differ from the remaining ten piers. In all these the granite masonry starts at low-water level, or 18 ft. below high-water level, with a diameter of 55 ft.; rises with a regular straight batter of 1 in $10\frac{1}{2}$ to a height of 12 ft. 8 in. above high water, where the diameter is 49 ft., and terminates in a necking and a coping course with a somewhat rounded top at exactly 18 ft. above high water. The courses of granite, of which there are nineteen, are rock-faced, while necking and coping are of dressed granite, and they vary in thickness from 21 in. in the lower to 16 in. in the upper courses, while above these the necking is 19 in. and the coping about 3 ft. 6 in. thickness.

TABLE No. VIII.—CIRCULAR GRANITE PIERS.—TABULAR STATEMENT OF QUANTITIES.

ALL EXCAVATION—CONCRETE, RUBBLE, AND BRICKWORK IN CUBIC YARDS. GRANITE IN CUBIC FEET. STEEL, IRON, AND CAST IRON IN TONS, CWTS. AND QRS.

Piers. Q.—Queensferry. G.—Inchgarvie. F.—Fife.		Excavation.	In Foundations below Low Water.			In Circular Pier.			Steel.		Iron.		Cast-Iron Anchor Plates.
			Concrete.	Brick-work.	Rubble.	Rubble.	Granite.	Brick-work.	Cutting Edge of Caisson, &c., Plates.	Holding-down Bolts.	Caissons.	Belts.	
									Tons cwts.	Tons cwt. qrs.	Tons cwt.	Tons cwt	Tons cwt.
Q. N.E.	Mud and boulder clay.	6827	9601	Nil	Nil	2376	13,021	Nil	52 7	9 6 3	399 0	9 9	12 12
Q. N.W.		6271	7547	1105	,,	2376	14,543	,,	52 7	9 6 3	454 18	9 9	12 12
Q. S.E.		6651	7361	Nil	,,	2305	13,237	,,	52 7	9 6 3	338 5	9 9	12 12
Q. S.W.		6372	7089	,,	,,	2305	13,237	,,	52 7	9 6 3	340 7	9 9	12 12
G. N.E.	Whin-stone rock.	755	Nil	,,	236	2300	13,237	,,	Nil	9 6 3	24 3	16 14	12 12
G. N.W.		324	Nil	,,	603	2300	13,237	,,	,,	9 6 3	38 10	17 1	12 12
G. S.E.		1054	5635	626	Nil	2300	13,237	,,	95 16	9 6 3	334	13 6	12 12
G. S.W.		831	6576	807	,,	2300	13,237	,,	95 16	9 6 3	300 11	13 6	12 12
F. N.E.	Whin-stone rock.	438	Nil	Nil	264	854	6484	,,	Nil	8 12 2	Nil	8 12	12 12
F. N.W.		444	,,	,,	481	494	6842	350	,,	8 12 2	,,	8 14	12 12
F. S.E.		1004	,,	,,	836	2300	13,237	Nil	,,	9 6 3	48 2	20 9	12 12
F. S.W.		823	,,	,,	200	2300	13,237	,,	,,	9 6 3	21 17	16 13	12 12

The latter two courses are of Cornish granite, the others of Aberdeen granite, both light grey in colour. The blocks of rock-faced granite have the edges dressed to the batter of the pier, and to horizontal and vertical joints. The courses are alternately headers and stretchers, with a bond of not less than 9 in. The joints are not more than $\frac{1}{4}$ in. wide, and are pointed from the outside with pure cement.

The hearting is principally of flat bedded Arbroath rubble, but a large number of whinstone blocks roughly squared were also built in. In building the pier the rubble masonry closely followed the setting of the granite, and both vertical and horizontal bond was strictly observed. Between the concrete in the foundation and the rubble masonry in the piers bond was also established by large blocks of whinstone squared to obtain proper bedding. (See Figs. 54 and 55.) At this point a wrought-iron belt 56 ft. 6 in. in diameter, 18 in. in depth and $\frac{3}{8}$ in. thick, made in sections and rivetted together, was placed and built in. A second belt of similar strength, but only 43 ft. in diameter, was built in about 2 ft. below high water, and a third belt of double strength, or $1\frac{1}{2}$ in. thick and 39 ft. in diameter, was built in just behind the coping course. All these are shown in Fig. 54.

When the level 7 ft. below high water was reached a temporary timber stage was erected and carried to the level of the underside of the fixed bedplate about 17 ft. 6 in. above high water. Upon this a templet of the bedplates made of light angles and $\frac{1}{2}$-in. plate in four sections bolted together, which had all the holes for the holding-down bolts in it, was laid, correctly centred and screwed down. The bolts with anchor plates supported by nuts were then carefully set up and built into the rubble masonry, a space of a few inches being left round each bolt to admit of subsequent adjustment. This is very distinctly seen in Plate VII.—Inchgarvie north-east pier. The building of the pier was now continued, the position of templet and holding-down bolts being frequently checked to insure correctness.

From the plan it will be seen that the coping course consists of alternate headers and stretchers.

The top or crown of the pier is slightly spherical, and is built up of blocks of dressed Aberdeen granite from 17 in. to 18 in. in thickness. The blocks fitting into and adjoining the coping course were all cut to wooden templets sent, the remainder being arranged in straight courses. The blocks project from 6 in. to 12 in. under the bedplate, a recess being cut out to receive the latter. The remaining space under the bedplate is made up with Arbroath rubble masonry, and in one case with a tolerably thick layer of Staffordshire blue bricks built in cement.

The mortar used in building the piers was throughout of one part cement and two parts of sand, and was mixed in a pugmill close by. At first hand cranes only were used in the building, but steam cranes were substituted as being more handy and expeditious. Both granite blocks and rubble were handled and set by means of pointed chain-clips, holes being picked for the purpose.

The holding-down bolts in each pier were forty-eight in number, in four rows of twelve each. They are set at 2 ft. 9 in. and 7 ft. respectively to each side of the centre line, and are longitudinally about 3 ft. apart. Owing to the inward set of the bottom members in cantilevers, rather more than half of the bolts are set in a line parallel to the centre line of the bridge, the remainder following the deviation of the bottom member. In order to bring the largest possible mass of masonry into play, the four centre-bolts of each outside row are bent outwards, as shown in Fig. 54, and to prevent any tearing action upon the masonry which would be produced by the bolts being drawn tight at top, cast-iron shoes are inserted at the point of kinking, and these are held together by a pair of angle-bars to each pair of bolts. (Figs. 56, 57, 58, and 59.) The holding-down bolts are of a special steel. They are $2\frac{1}{2}$ in. in diameter, with an enlargement to 3 in. at both ends, where a screw thread is cut upon them. They are about 25 ft. long. The anchor plates are 2 ft. square with a long boss, stiffened by four diagonal ribs, and are held by an ordinary nut. The bolts received several coats of tar before being built in.

When the masonry had been carried to within about 8 ft. of the top the templet had to be removed to allow the rubble to be placed in position, but it was replaced from time to time, and the position of the bolts frequently checked. As the heads of these bolts fitted in the lower bedplate without any play whatever, it was necessary that their position should be absolutely correct.

When the masonry had got up close to the under side of the bedplate the bolts were again set with the greatest care, and the spaces left round them were filled up with cement grout to within about 4 ft. of the top.

Immediately underlying the bedplate, and with a view of making a perfectly level bed for the same, cast-iron blocks, 12 in. square and 4 in. thick, with a hole which only just admitted the head of the bolt, were placed, carefully levelled by instrument and set in cement, the spaces all round and between these being levelled to the thickness of 1 in. with cement. In addition to the round hole in each block, a slot was cut and a taper wedge driven hard into this and against the screw thread. This was done to prevent torsion in the bolts when the large upper nuts required to be drawn tight. On the bed thus prepared the lower bedplate was laid in the manner hereafter described. The heads of the holding-down bolts, as well as square washers, nuts, &c., are shown further on in connection with the bedplates.

Raising of the Approach Viaduct Girders and Underbuilding of the Piers.

The height to which the piers of the approach viaducts had to be carried was 130 ft. 6 in. above high water, and the question how best to deal with both the erection of the girders and the building of the piers was ultimately settled by deciding to put the girders together at any convenient level, and make the lifting of these and the building of the masonry a simultaneous operation.

The fifteen spans of 168 ft. each, of a total weight of slightly over 3000 tons, or, roughly, 200 tons per span, were built under a sub-contract by Messrs. P. and W. McLellan, of Glasgow, the contract including their being put together and rivetted up on the staging provided at the Forth Bridge.

The girders are of the ordinary double-lattice girder type, consisting of two parallel girders at 16 ft. centres, having trough-shaped top and bottom booms and side bracings consisting of intersecting diagonal struts and ties. The trains run on the top, the troughs of the two outside rails forming the top booms of the girders. Each span is divided into eight bays of 21 ft. each, which is also the height of the girders, and at the intersection of struts and ties a vertical support is carried upwards to the top boom. A cross-bearer occurs every 7 ft., or three to each bay, and carries not only the two troughs for the inside rails, but also projects beyond the two outside troughs for a distance sufficient to form a 4-ft. path on each side, and to support the brackets of the wind fence. The floor is made up of buckle plates. The bottom booms of the girders are braced laterally by lattice girders intersecting at centre, and there are also vertical cross-bracings of double angles at suitable distances.

Two spans are made continuous, and expansion joints are provided over every second pier. The ends of all the girders rest on sliding bedplates, no rollers being used. The details of these girders call for no special remark. They were originally intended to be built of wrought iron, but, in view of the cheapness and excellent quality of steel, the latter material was ultimately adopted.

Various circumstances combined to fix the height of the staging on which these girders were put together.

On the Fife shore the high ground upon which the cantilever end pier and piers 10 and 11 were founded necessitated the putting up of staging to a height of 41 ft. above high water; the four piers 10 to 13 having by September 30, 1883, been brought up to 37 ft. above high water.

On this staging the girders were erected and rivetted up, the last length next to the north cantilever end pier and nearly half the length of the span between pier 13 and the abutment being left out, however, for the time being. The cantilever end pier had been built up to a considerable height, and between pier 13 and the abutment a public road passed at a considerable height above the then level of the staging.

As the mode of raising the girders will be more fully described in connection with the south approach viaduct, it will be sufficient to state here that, in order to raise the end of the girders nearest the cantilever end pier, a set of strong columns were built up and lengthened by degrees as the lifting proceeded; and upon these the hydraulic cylinders were placed. The mode of raising was similar to that employed for the large platforms of the central towers, and fully described there. Upon piers 10, 11, 12, and 13 the lifting proceeded in the usual way, but, not far from the abutment, a set of columns similar to those at the

TABLE No. IX.—Viaduct Piers and Cantilever End Piers.—Tabular Statement of Quantities.
All Figures for Concrete and Rubble in Cubic Yards—for Granite in Cubic Feet.

—	Foundations.		Granite Masonry Piers.				—
	Concrete.	Rubble.	Concrete.	Rubble.	Granite.	Freestone Bond Courses.	
South Viaduct.							
Pier No. 1	246	nil	42	314	5526	not stated	
,, 2	176	nil	322	318	5591	1793	
,, 3	151	nil	413	607	10002	3425	
,, 4	73	nil	540	607	10002	3392	
,, 5	72	nil	622	607	10002	3513	
,, 6	80	nil	685	607	10002	5912	
,, 7	228	nil	936	607	10002	5993	
,, 8	320	nil	973	607	10002	5946	
,, 9	706	nil	973	607	10002	5987	
South Cantilever End Pier ...	2167	295	1753	3420	43984	39078	162 of blue brick
North Viaduct.							
North Cantilever End Pier ...	205	nil	774	2[illegible]20	32944	17305	37 of blue brick
Pier No. 10	69	nil	90	598	11610	not stated	
,, 11	52	nil	130	611	11814	,,	
,, 12	273	nil	204	508	11756	1954	
,, 13	340	nil	419	610	11789	1019	

Table No. X.—*Showing Quantities of Masonry Piers, Arches, and Abutments certified for up to November 30, 1889.*

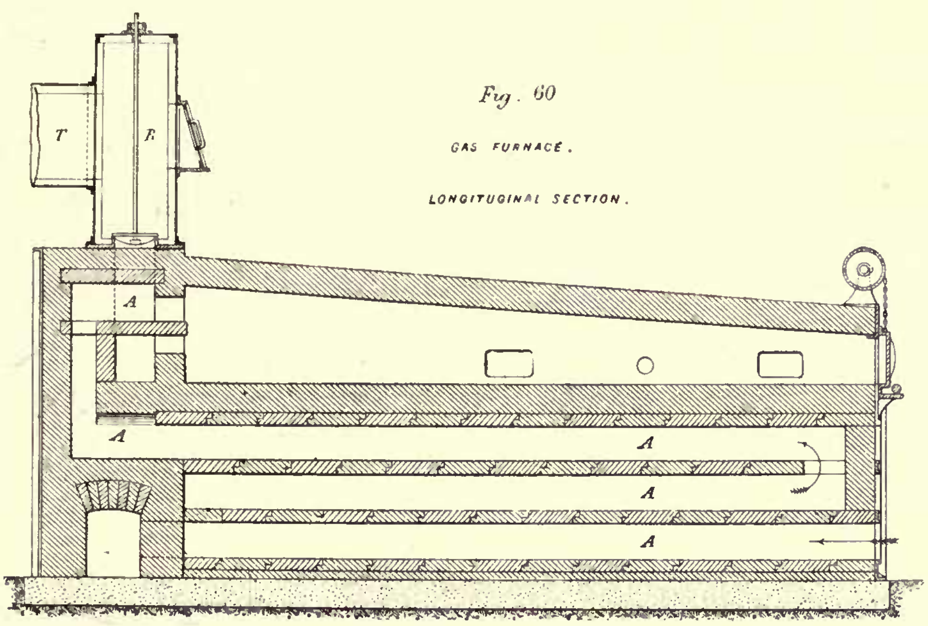
—	Cubic Yards.	Cubic Feet.
Concrete	64,315	
Rubble	48,356	
Rock-faced granite ...	...	494,642
Dressed granite ...	...	140,756
Bond courses... ...	...	105,180
Totals	112,671	740,578

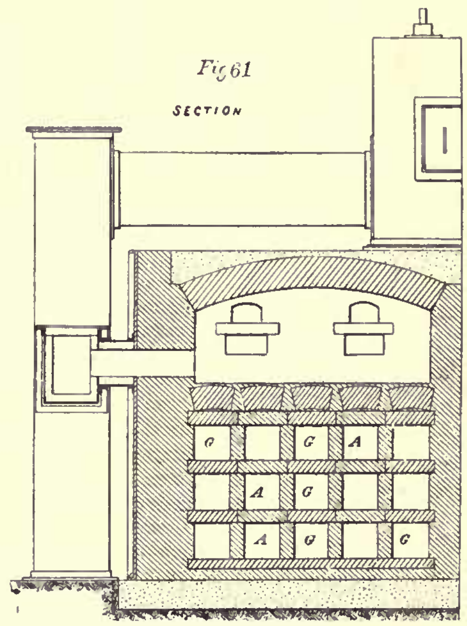
Grand total, 140,160 cubic yards.

Note.—The quantities of masonry, &c., for abutments and arches are not given in the detail statement above, but they are included in the totals here stated. Some 7500 cubic feet of granite for completion of the cantilever end piers have to be added.

VIII.—were also stowed the hardwood packings and other necessaries for the lifting work. All these things put a great deal of extra weight on the girders, but as neither buckle-plates nor wind-fence had been put on as yet, the weight did not greatly exceed that of the finished girders.

The mode of procedure was as follows:—Hardwood packing in slabs of varying thickness, from





HEATING FURNACE FOR PLATES.

other end were used. When the girders had been raised to a point above the cantilever pier and the abutment (as far as these had by then been built) the two ends were joined on, and the completed girders raised up to their final position. The first lift of these girders was made about the middle of October, 1885, to level 42 ft. above high water, and the last lift to level 130 ft. 6 in. above high water on February 15, 1887.

The connections of the permanent way on this viaduct with that on the cantilever at one end and with that on the masonry arches at the other end are made by means of expansion joints, identical with those used at the fixed ends of the Fife and Queensferry central connecting girders, and fully described in connection with the latter.

On the Queensferry shore, owing to the rising ground between pier 3 and the south abutment, the girders had also to be built at different levels, and were only joined when the various portions had arrived at the same level. The seven spans from pier 3 to south cantilever end pier were all built on staging erected between the piers, and rising to a few feet above the masonry, in order to allow the lifting rams and lifting girders to be placed between piers and viaduct girders.

Piers 3 to 5 had been brought up to level 18 ft. above high water early in January, 1884, pier 6 in March, 1884, pier 7 in October, 1884, pier 8 and cantilever pier in February, 1885, and pier 9 in June, 1885. The delays which occurred were due to difficulties and to a larger amount of work in connection with the construction of the cofferdams and the building of foundations and lower portions of these piers; but so soon as any of them were completed, the staging between was built, and a start made with the erection and rivetting of the viaduct girders. Thus it was possible to have everything ready and to commence lifting early in the month of May, 1886.

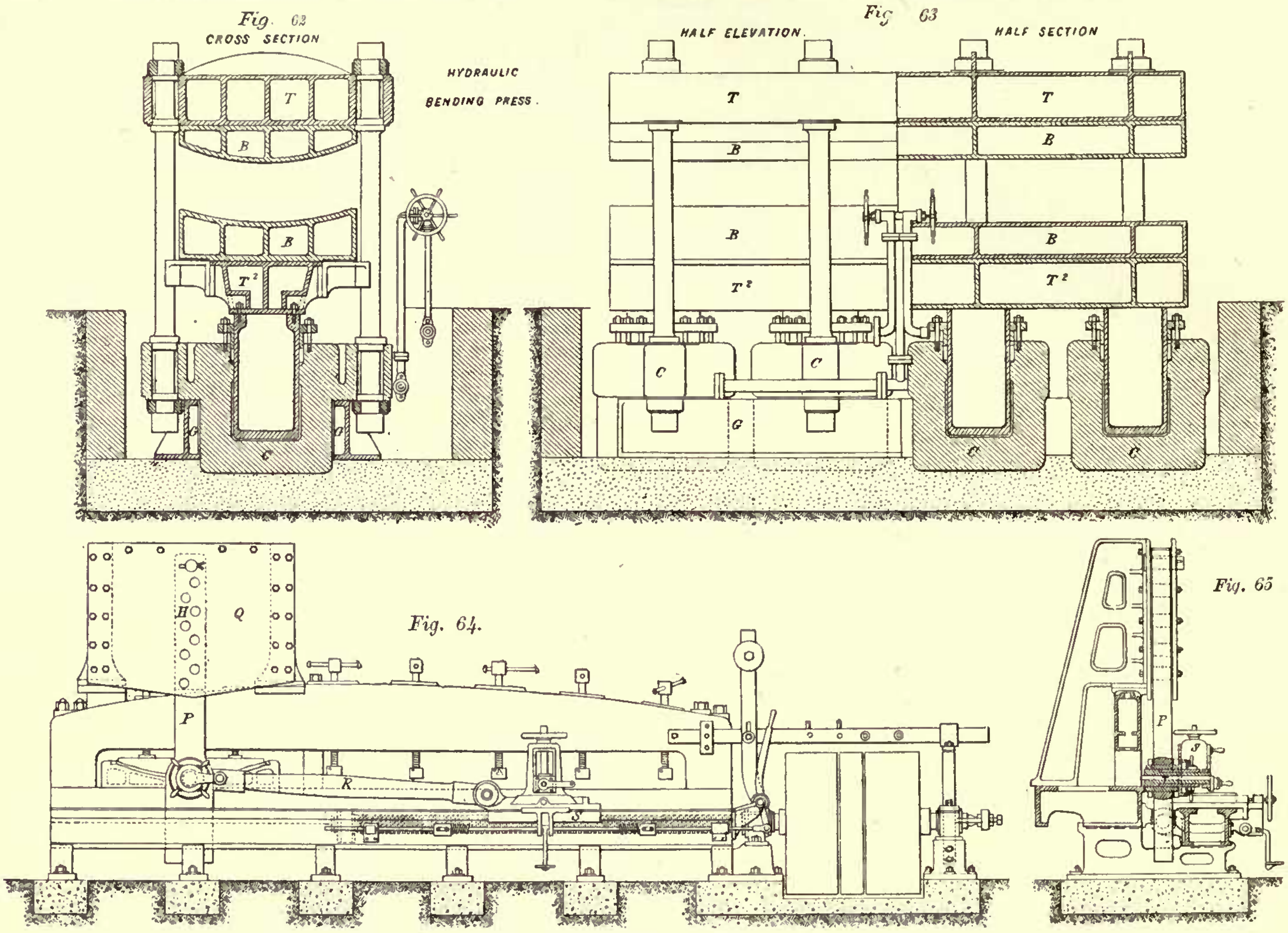
Piers 2 and 1 had in the mean time had their foundations laid and their masonry raised to about 43 ft. above high water, while the abutment on top of the hill was raised to 115 feet above high water.

For the purpose of raising the viaduct a box girder of great strength, about 22 in. deep, 2 ft. 6 in. wide, and some 24 ft. in length, was placed directly under the girder end-posts—that is, along the centre of the piers. During the raising of the girders temporary connections had been made between girders at these places where expansion and contraction could take place. Immediately under each main girder a hydraulic ram, 14 in. in diameter and 16 in. stroke, was inserted in the box girder, and was made a fixture in it. There was thus a length of girder of about 3 ft. outside each cylinder for packing. All the cylinders were connected with force-pumps, which could produce a pressure of 35 cwt. per square inch, the pumps being placed within the bottom booms of the viaduct girders, which were completely decked over and used as a road, being fenced on each side, and having two narrow-gauge lines laid down on it, during the time of lifting. Round each pier a timber platform was suspended from the girders, so arranged that its planking could be brought up close to the masonry as the piers diminished in size with the ascent. On this platform—which is clearly shown in Plate 1 in. up to 12 in., was placed under the girders in two or three places, and by means of long wedges, one worked from each side, every lift was closely followed up to prevent sudden drops, should the hydraulic presses give way. When a lift of 1 ft. had thus been made, the girder was packed and the ram was fleeted—that is, drawn back into the cylinder—and a hardwood block with a strong steel plate on top was underlaid and a further lift made.

At first it was attempted to raise the whole mass of over 1400 tons at once on all points, but this was not found to work very well, and it was then arranged to work 3 in. at the time only, and lift on each pier in succession. No accumulator was used, but the pumps were just kept going until the girders were up. As a rule the lifts were of 3 ft. 6 in. at the time for two courses of masonry, but at times a foot more or so was done, according to requirements.

With the last lift on each occasion the packing was so arranged as to occupy the least room upon the masonry last done, and the masons then at once proceeded to set the granite facing and build the rubble backing in every place that they could get at, taking good care to leave the work so as to make sufficient bond with the remainder. After allowing forty-eight hours for the setting of the new work, the weight of the girders was shifted on to packings laid on the new work, and the remaining portions of the two or three courses, as the case might be, were then built in. After due allowance for the setting of this work also—another forty-eight hours generally—a fresh lift was made.

All materials for building were raised to the girder level by means of two hoists stationed at either end, and the materials so raised were run on trollies by boys or drawn by Shetland ponies to the places



BENDING PRESS FOR PLATES AND MACHINE FOR PLANING ENDS OF CURVED PLATES.

where they were required. Thus granite blocks, Arbroath rubble, and mortar, were all prepared on the jetty below and lifted up.

To assist the masons in their work of laying granite and rubble an overhead traveller was placed to each side of every pier. All these travellers were worked by friction gear and clutches, both for hoisting and lowering, or for travelling, an endless wire rope being run along the girders from end to end, driven by the same engines which drove the pumps during lifting.

When the seven spans had thus been raised to 47 ft. above high water, the next two spans from pier 3 to pier 1—which in the meantime had been erected on staging passing over the Edinburgh-road—were joined on, and the further lifting proceeded with in the same manner as before. The last span from abutment to pier 1 had meanwhile been erected on staging at level 119 ft. above high water, and was joined on when the other girders reached that level, the complete viaduct being then raised through the remaining 11 ft.

The first lift at South Queensferry was made from level 23 ft. above high water in May, 1886.

Level 47 ft. above high water was reached August 10, 1886.

Level 91 ft. above high water was reached February 15, 1887.

Level 119 ft. above high water was reached June 14, 1887.

Level 130 ft. 6 in. or top was reached August 7, 1887.

No mishap of any kind occurred in the course of this work, and in no case did the granite facing or rubble backing show the least sign of giving way during the underbuilding of the piers under this considerable load.

After the girders had reached the tops of the piers the cross girders and hydraulic rams were removed and the bedplates substituted.

In all cases the thirteen viaduct piers had the hearting constructed of concrete up to the level at which the girders were built, but from the time lifting was done Arbroath rubble was used exclusively, as it was feared that the concrete could not set sufficiently hard in the time allowed between the lifts, while the Arbroath rubble masonry set firmly and solidly in about thirty hours.

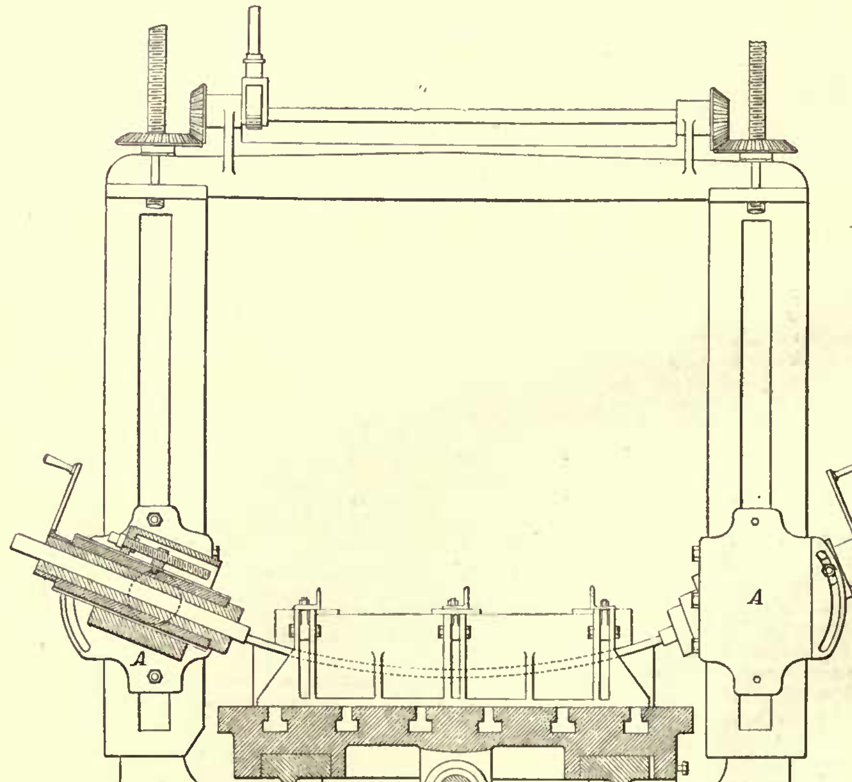


Fig. 66. Machine for planing edges of curved plates.

Very little staging was used in this mode of erecting, most of the timber being used over and over again, for as soon as a girder was rivetted up and could carry itself across the span the staging was removed from under it, and was transferred a span further forward.

After the piers were in position the temporary connections at the joints where provision had been made for expansion and contraction were removed, and the remaining buckle-plates on the top and the wind-fence on both sides were put on.

After several coats of paint had been put on the

girders they were left until the time when the permanent way was required to be laid down. One of the views on Plate VIII. shows the girders at full height.

THE STEEL.

With the exception of a few hundred tons of cast-iron washers and anchor-plates in the piers,

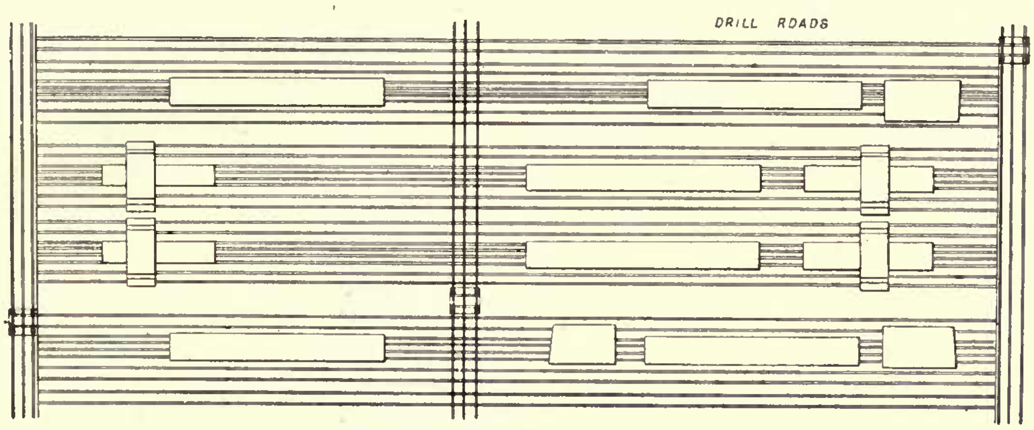


FIG. 67. PLAN OF DRILL ROADS.

Fig 68

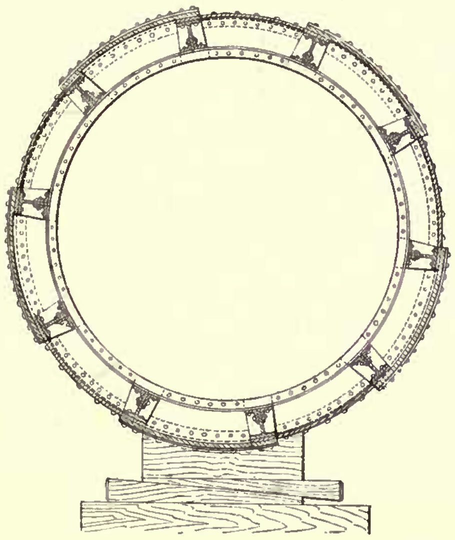


Fig. 69

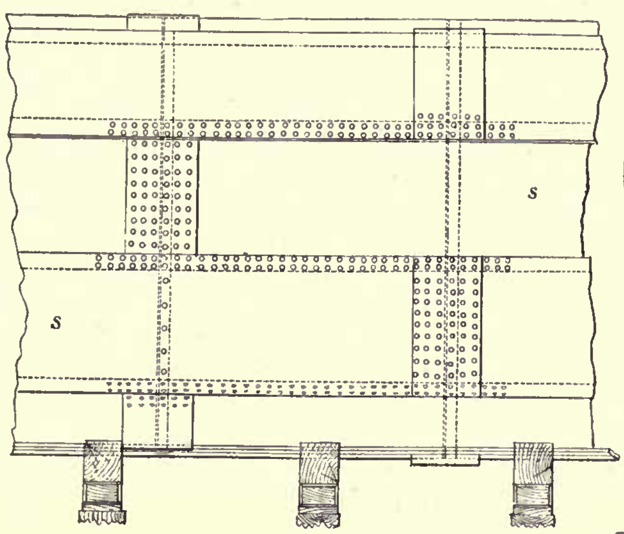


Fig. 70

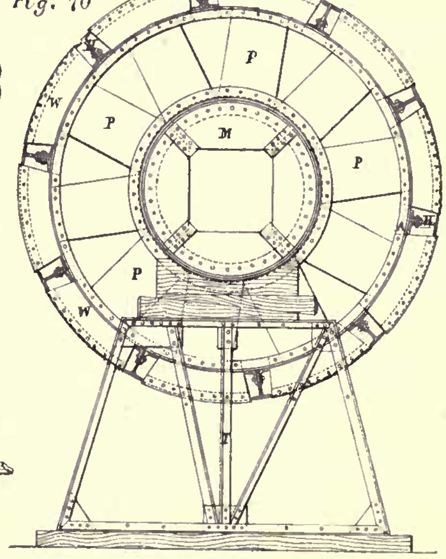
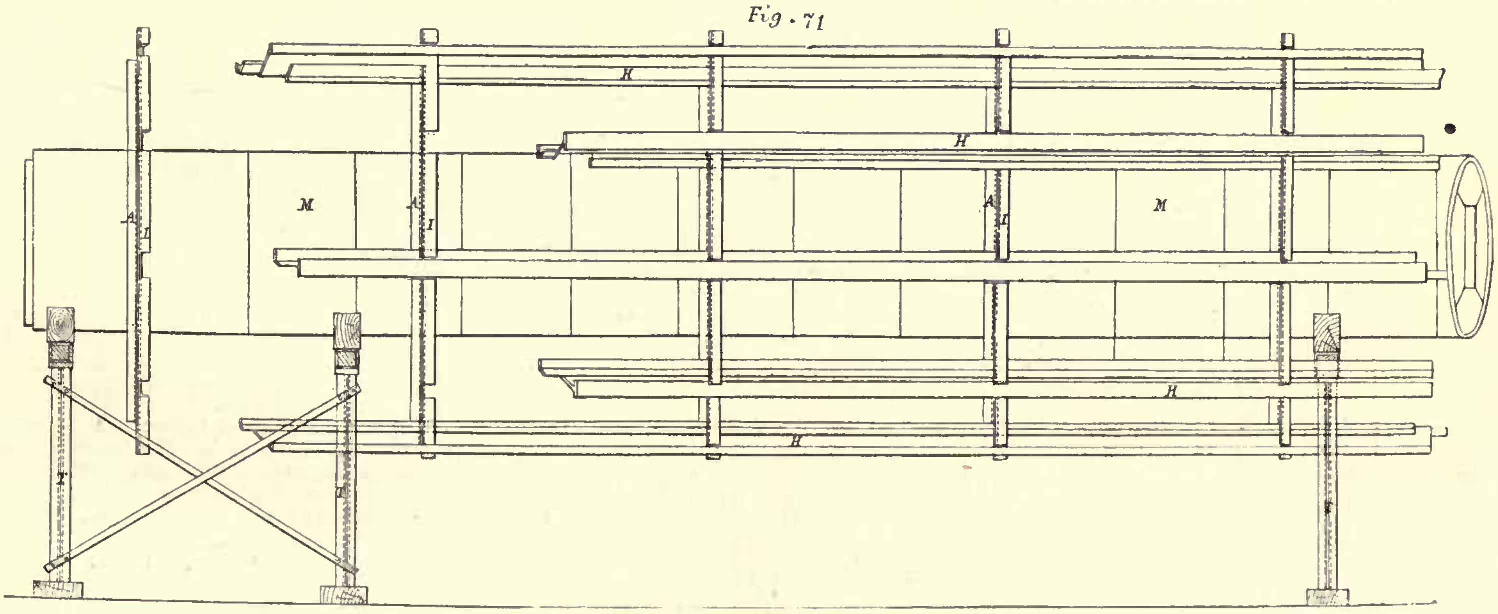


Fig. 71



BOTTOM MEMBER ON DRILL ROAD.

and about 2000 tons of deadweight consisting of cast-iron bricks laid in asphalt—which are placed in the ends of the two fixed cantilevers terminating in the cantilever end piers—the whole superstructure, from holding-down bolts to the ventilators on the extreme top of the vertical columns, and from the granite arches at one end to those at the other end, is built of steel.

The choice of a material for constructing a bridge of novel design, of extraordinary magnitude, and exposed during erection to the effects of powerful atmospheric disturbances, must have been the subject of much anxious thought and reflection to the engineers. But, in whatever way the decision was arrived at, there can be no two opinions that the choice was a happy one. From beginning—and probably a long time before the beginning of this work—to the end, this steel was subjected to every conceivable test, both in a properly scientific manner for purposes of research or investigation, and in an entirely unscientific manner by workmen, whose only excuse can be that they did not know better. But in all cases the steel stood the test, and a more uniform, a more homogeneous, and more satisfactory material could not be wished for. To only quote one instance, the writer has in his possession several pieces of scrap from the shearing-machine, picked up promiscuously and placed under an ordinary diamond-headed drill about 1 in. in diameter. A hole was drilled about $\frac{3}{4}$ in deep, and the machine stopped while yet the feed was on, the result being one single corkscrew shaving, about one yard in length, started from the very moment the drill touched the steel and attached yet by the end to the piece of scrap out of which it was bored. It would not, probably, be straining a fact to assume that this behaviour of the steel under severe tests had a great deal to do with the confidence with which the workmen regarded every portion of the structure, and with their belief that no possible load they could pile on the temporary platforms could by any chance bring about a collapse. It is true that, in the early days of plate-bending, some thick plates broke near the edges in a seemingly mysterious manner, but the investigations made and the reasons adduced in connection with these fractures were sufficiently convincing to allay any feeling of distrust.

The Board of Trade stipulations in regard to steel for structures, do not go further than to lay down the rule that the maximum working stress should not exceed one-fourth of the ultimate breaking strain of the steel. No difference is made between the tensile and compressive stresses, nor is any regard paid to the differences between stresses due to dead load or live load—alone or in combination—nor to the circumstances arising from changes, occurring frequently or rarely, in the nature of the stresses.

The engineers therefore laid down, after consultation with the Board of Trade and with their approval, certain rules in regard to the stresses admissible under varying circumstances.

For tension members the steel was to have an ultimate resistance of not less than 30 nor more than 33 tons per square inch, with an elongation in 8 in. of at least 20 per cent. For compression members a resistance not less than 34 tons nor more than 37 tons per square inch, with 17 per cent. elongation.

With regard to varying stresses for a load varying between nil and a maximum, 20 tons per square inch of section to be assumed as the ultimate

TUBE DRILLING MACHINE ON DRILL ROAD.

Fig. 72.

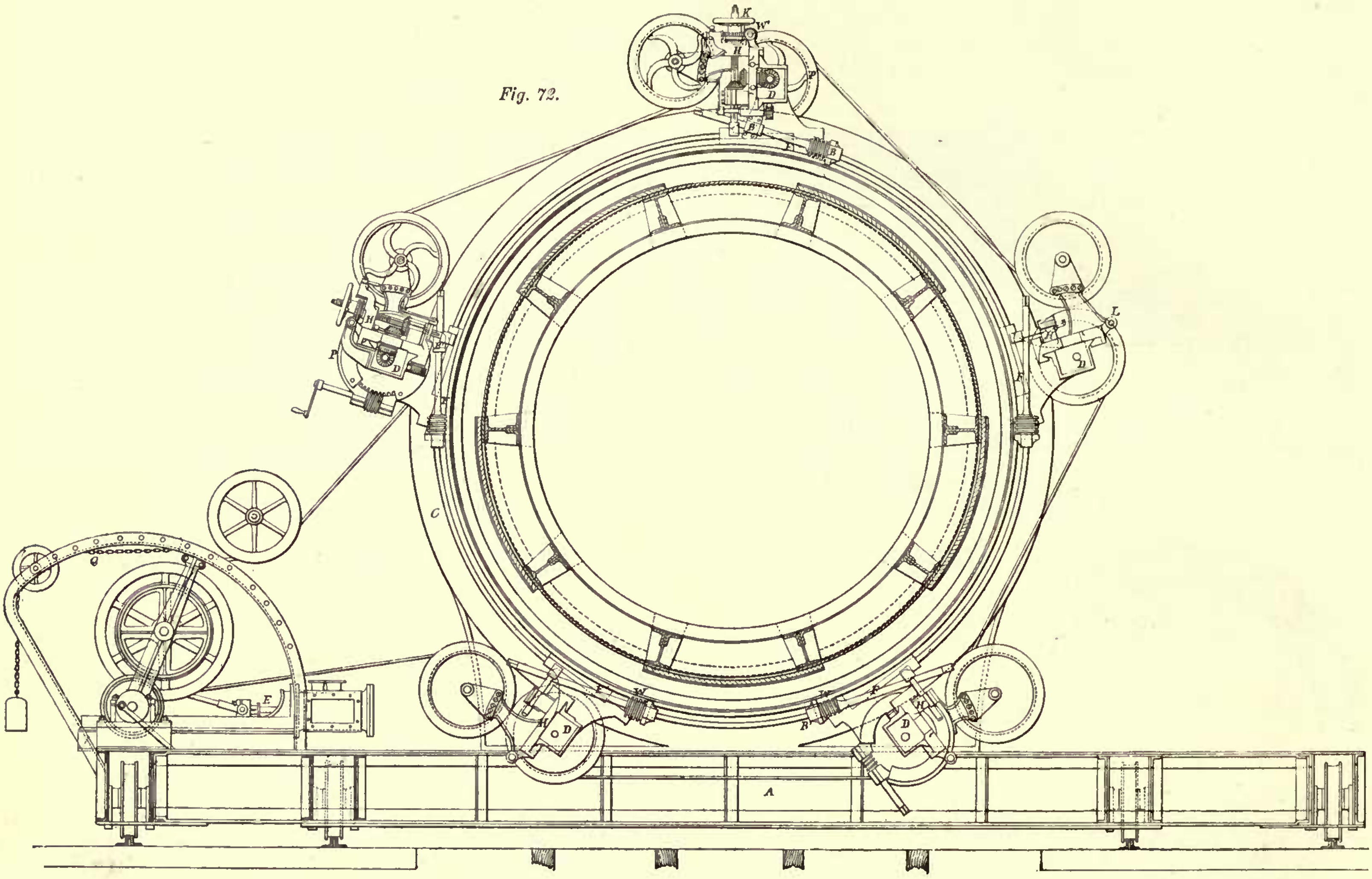


Fig. 73

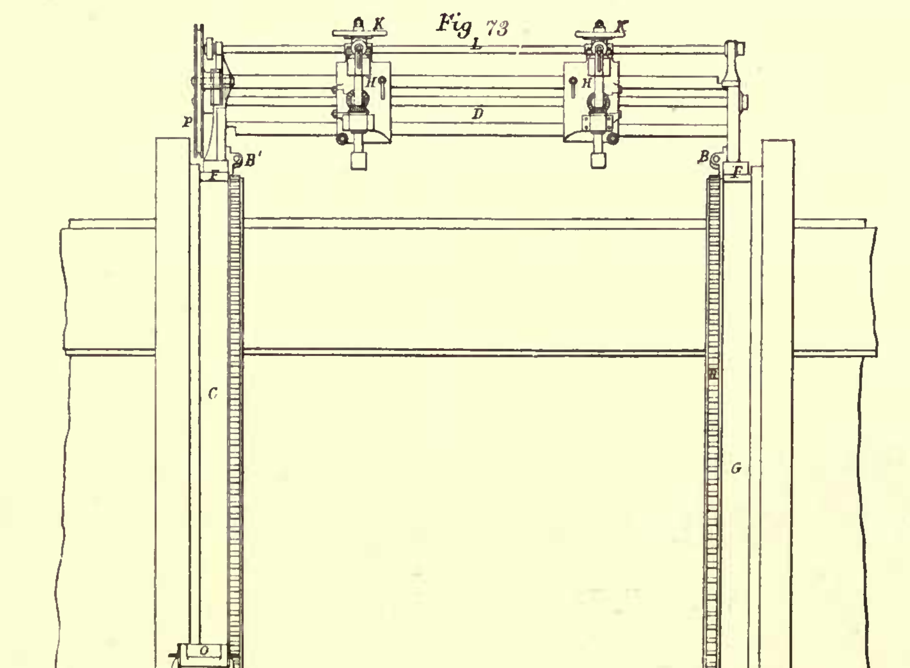
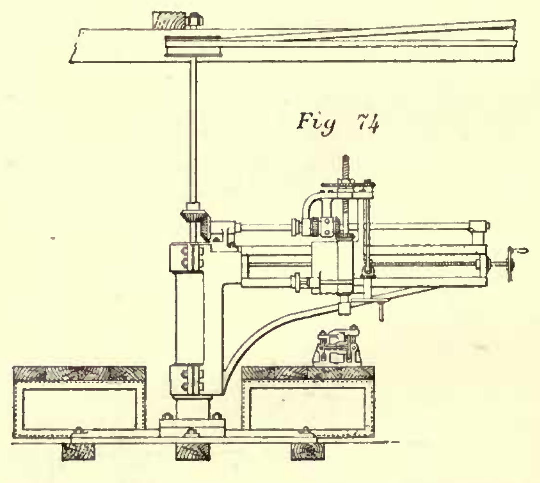


Fig 74



strength if the change occurs frequently, and $22\frac{1}{2}$ tons if occurring rarely.

For stresses alternately tensile and compressive, the ultimate stress to be 10 tons if frequent and 15 tons if seldom, one-third of the ultimate strength to be considered the working stress.

Rivet-steel to have an ultimate strength of 27 tons per square inch, with 30 per cent. of elongation, and shearing resistance to be from 22 tons to 24 tons per square inch.

Cast steel to have an ultimate tensile strength of 30 tons, with 8 to 10 per cent. elongation.

For tension members the sectional area of the rivets in the joints to be $1\frac{1}{2}$ times the useful section of the boom.

For compression members the area of rivets in butt-joints to be half the useful section of the member.

The original estimate gave the quantity of steel required for the Cantilever Bridge (not including approach viaduct spans) as 42,000 tons. Of this quantity the Landore Works near Swansea in South Wales, of Messrs. Siemens, supplied 12,000 tons, and the Steel Company of Scotland, from their

Blochairn and Newton Works near Glasgow, the remaining 30,000 tons. For the alterations made subsequently in the design, and the increase of section in various parts, a further quantity of about 16,000 tons was required, about one-half of which was supplied by the Steel Company of Scotland, and the other half by Dalzell's Iron and Steel Works at Motherwell, near Glasgow. The steel for the viaduct spans, about 3200 tons, is not included in the figures given above. The Clyde Rivet Company, Glasgow, supplied about 4200 tons of rivets.

With regard to tests, one plate out of every fifty, picked out promiscuously, had a strip cut out of it which was planed on all four sides and tested for tensile stress in a 50-ton testing machine. The same proportion was observed in the case of bars.

For transverse or bending tests a piece was cut off every plate and every bar, about $2\frac{1}{2}$ in. wide, and tested by being bent under the press to a radius of $1\frac{1}{2}$ in. thickness with the ends of the test-piece closed. As regards the steel supplied by the Steel Company of Scotland, all plates were rolled at the Blochairn Works, and all bars at the Newton Works.

Failures of the steel under test were of the rarest occurrence.

All steel was manufactured by the Siemens-Martin open-hearth process, and all plates, bars, tees, angles, and other pieces, were cut to length and shape as ordered and thus delivered at the works.

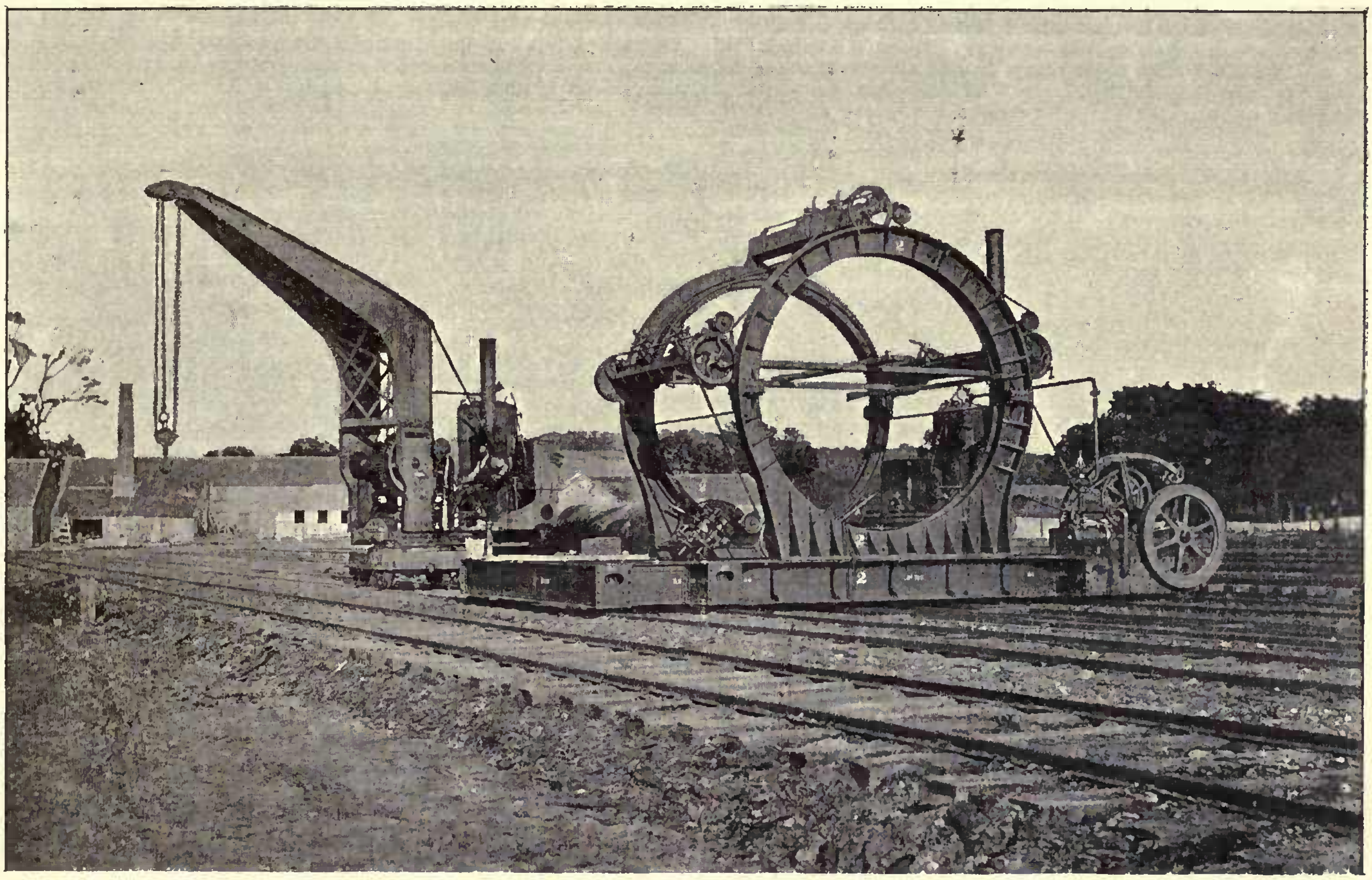


Fig. 75. Tube drilling machine and travelling crane on drill road.

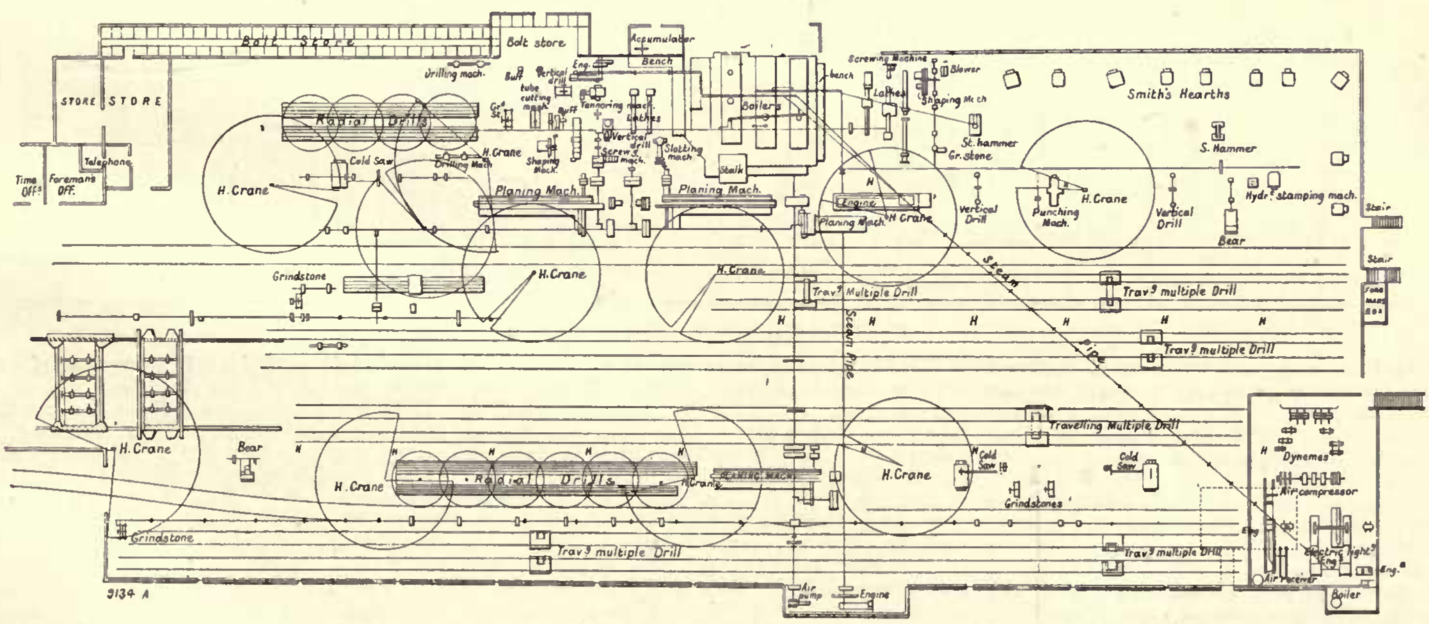


Fig. 76. Plan of No. 1 drill shed.

About 6 per cent. of the total steel delivered was returned as scrap, or between 3000 tons and 4000 tons. A certain proportion of the steel delivered was used for temporary purposes only, and this will account for the difference between the total quantity delivered and that erected.

Drawings.

All detail drawings were made at the drawing offices attached to the works and submitted to the engineers previous to being passed into the workshops. If necessary, full-size drawings were made on the blackened floor of the large drawing loft, and from these all templates were made in wood. The templates were carefully cut to size, all holes drilled in them, and all necessary information and description branded upon the template in clear type. In certain cases, such as bracing bars, which recur several hundred times over, some of the bars themselves were used as templates. For the erection of the superstructure the tracings were transferred to sheets prepared by the ferro-prussiate process, by which the only part of the paper remaining white is that which underlies the full or dotted lines of the tracings. The drawing is, therefore, of white lines upon a deep blue ground.

Workshops.

Two principal divisions were made in regard to the construction, namely, between the tubular

members and the latticed girders. The former were done in the upper or No. 2 shed and on the drill-roads adjoining it; the latter, in the lower or No. 1 shed. Considering that as much of the work as could possibly be done was to be drilled with all parts put together, it will be at once understood that not only did the drilling form a most important part of the work, but also that a great deal of special plant designed for each particular purpose would be required. As a broad rule, therefore, all tubular members were put together and drilled through the various thicknesses at once, the only parts done separately being the portions of beams and diaphragms not in contact with the outer shell. In the lattice-girders the booms were drilled singly, on specially prepared beds, made up of timber blocks; or, if worth while, on cast-iron frames. The lattice-bars were drilled by other machines.

In the building of the tubular members the first work to be done was to bend the plates to the required curve. For this purpose the plates were put into a gas furnace (see Figs. 60 and 61), heated up to a bright red heat, and then passed into a hydraulic press, where, between two dies or saddles, they received the necessary curvatures. (See Figs. 62 and 63.) The plates were then placed aside in piles, covered with ashes, and gradually cooled down. However carefully this is done, some alteration takes place in the shape of the plates; and to remedy this the plates, when quite cold, were put into the hydraulic press once more and received a final setting. They were then placed into a planing machine (see Fig. 66), where the two long side edges were planed down to the required dimensions; while in another machine of simple construction the end edges were dealt with in the same manner. (See Figs. 64 and 65.) They were now ready to be built up into tubes on the drill-roads. (See Fig. 67.) Here a long cylinder, or mandrel with wings attached, was supported on a number of trestles, and round this mandrel the tube was built up, the diaphragms being bolted to the wings of the mandrel. (Figs. 68, 69, 70, and 71.) Meanwhile, the beams had been prepared and drilled with the angles attached by ordinary radial drilling machines in the shop. (See Fig. 74.) The beams were now bolted with their inner ends to the angle-iron rings of the diaphragms; and on the beams again, the inside, and later the outside, plates were fixed by means of ordinary clamps and by draw-washers. The underside of the tube was also supported by timber blocks built from the ground. The centre of the mandrel was now checked by means of a theodolite, and, if necessary, corrected. All was now ready for drilling, except, perhaps, that all holes in the lap-joints of the plates and those for the circular girders required to be marked. The drilling machine, specially designed for this work, was now brought forward. (Figs. 72, 73, and 75.) It consists of a wrought-iron carriage A running on a double line of rails on each side of the tube, and to it are fixed in the centre line of the tube two circular frames C C[1] about 10 ft. apart, and completely embracing the tube with about 6 in. of play all round. Upon the frames are placed five cross-girders D D, so arranged that by means of circular rack and worm B B they can work right round the tube, each girder carrying two spindles H H, which can run from end to end. On one side of the carriage is placed an engine E E and boiler, and the driving of the spindles is accomplished by an endless cotton rope. Thus arranged, the ten spindles point radially to the centre of the tube, no matter where placed. This machine was now pushed forward to the tube, timber packings being removed in front and replaced behind as the machine advanced, and drilling was carried on until all holes (about 100 per foot run) in the 8 ft. section were drilled. The machine was then moved forward to the next section. On the side to which the machine was moving new beams and plates were always added, while on the other side they were removed and taken to the stack-yard. Before being removed, however, every plate, every beam, angle, cover or strap was typed with distinguishing letters, which made it possible, at a moment's notice, to fix its position in the structure. In tubular members other than circular, the side frames in which the cross-girders which carried the boring spindles moved, instead of being circular, were of the same shape as the members themselves; and on flat surfaces, for instance, the spindles were thereby placed at right angles instead of radially.

Besides the machines here described there were a number of others, all for special purposes, each of which carried out its appointed work in a most efficient manner. Many different types of hydraulic presses for the shaping of bars or corner plates for the square-ended struts were used, and had constantly to be altered as circumstances required.

Drilling machines, similar only in respect of the fact that they drilled holes, and that they moved alongside the work which was made a fixture, were in use in the lower or No. 1 shed. (See Fig. 76.) These machines had at times ten boring spindles going at one and the same time, and there were on several of the machines as many as thirteen spindles available for use. These multiple drilling machines are shown in Figs. 77, 78, 79, and 80.

Here also an ingenious tool was in operation which cut the 3-in. round holes out of the lower bedplates, and which also cut the larger round holes 7 in. in diameter, and the oblong holes 11 in. by 7 in., with rounded corners (see Fig. 96), out of the upper bedplates. This machine consisted of a vertical spindle turned by worm and wheel, and upon this spindle was a saddle in which could move forward and backward a horizontal slide which carried a roller on top, and a cutting tool at bottom. The roller at top moved between two frames, which could be removed at will, and which had the same shape which it was desired the hole below cut by the tool should have. It followed therefore that whatever shape these frames had, the tool was obliged to follow and cut a hole the same shape. By placing the tool at different distances from the revolving centre while leaving the roller at the same distance, the size of the hole could be diminished or increased to any desired scale. A machine for planing the very long plates required in the lattice girders is shown in Figs. 81, 82, and 83. It will be noticed that it has an end saddle and tool as well, thus allowing two edges of the plate to be planed at one time. A further feature of the machine is the use of hydraulic rams for holding down the plate in lieu of the usual screws.

Here all the tension members, wind-bracing girders, bedplates, and the top junctions with flat

Fig. 77.

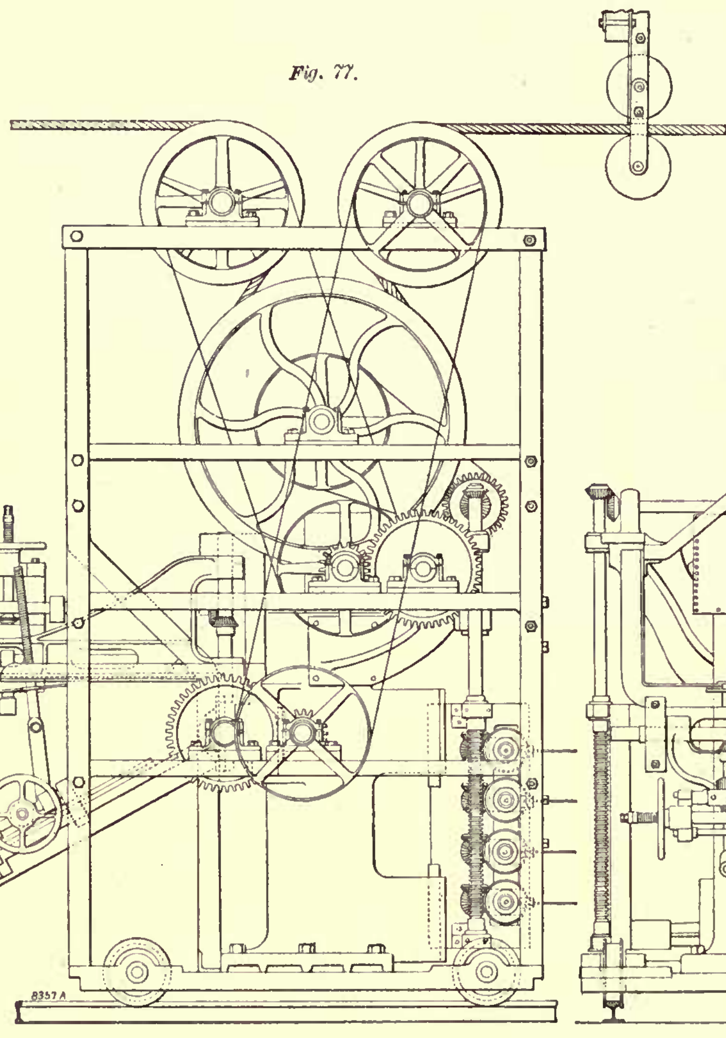
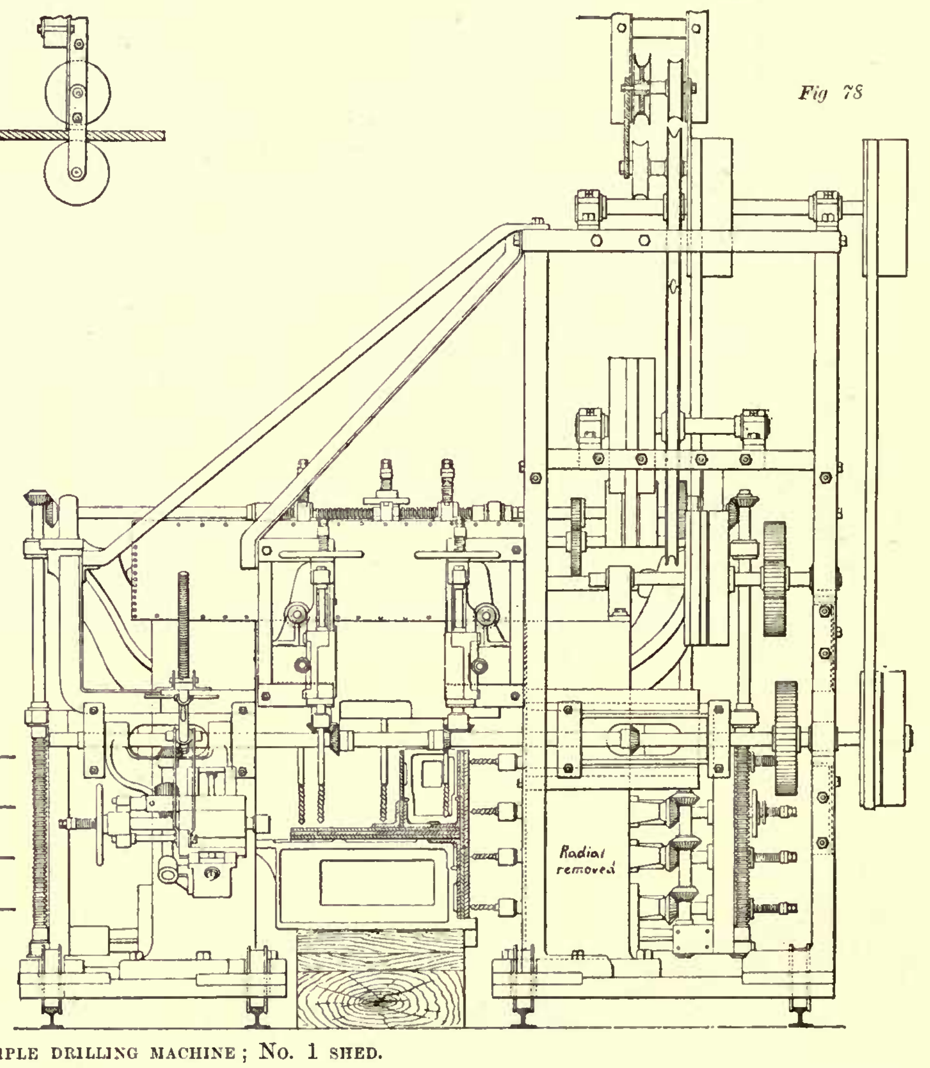


Fig 78



MULTIPLE DRILLING MACHINE; No. 1 SHED.

sides were put together and drilled, as also a mass of small detail work, and all the temporary girders used in the erection and in the stagings.

Outside these workshops and the drill-roads, many acres of ground were taken up with the building up and fitting together of the various girders, of which the single booms had been drilled in No. 1 shed. Thus a great portion of the internal viaduct was put together and a number of bracings which had to be templated in the first instance *in situ*, were done and multiplied. These portions of the internal viaduct were erected for one pair only, however, and in the others it was simply repeated.

The bottom junctions, or junctions between bottom members, struts and ties and wind-bracings in cantilevers, were laid down and finished on the drill-roads, while those of the top members with struts and ties were laid down and built in the field.

For the handling of the plates, beams, and other parts of the tubular members and the skewbacks and bottom junctions, powerful travelling cranes (see Fig. 75), some with curved jibs 40 ft. high, were used, and these could move about all over the drill-roads, being shifted from one line of rails to another by means of traversers. Ordinary derrick cranes worked by steam or by hand were also largely used.

In the shops, however, most of this work was done by hydraulic cranes of very simple construction, yet eminently adapted for their work. (See Figs. 84 and 85.) In many places they were so disposed that material could be lifted and swung round from one to the other so as to traverse the whole length and breadth of the shop. (See Fig. 76.)

A large amount of rivetting was done in the yards and the field in the case of such portions of the girders as the booms of the tension members, and later on, whole portions of the rectangular wind-bracing girders, of which then the joints only required rivetting up after they were erected. Much rivetting was also done upon the longitudinal beams and the diaphragms in the tubular members. All this rivetting was done by hydraulic machines, and could be finished at an extremely cheap rate.

Fig. 79.

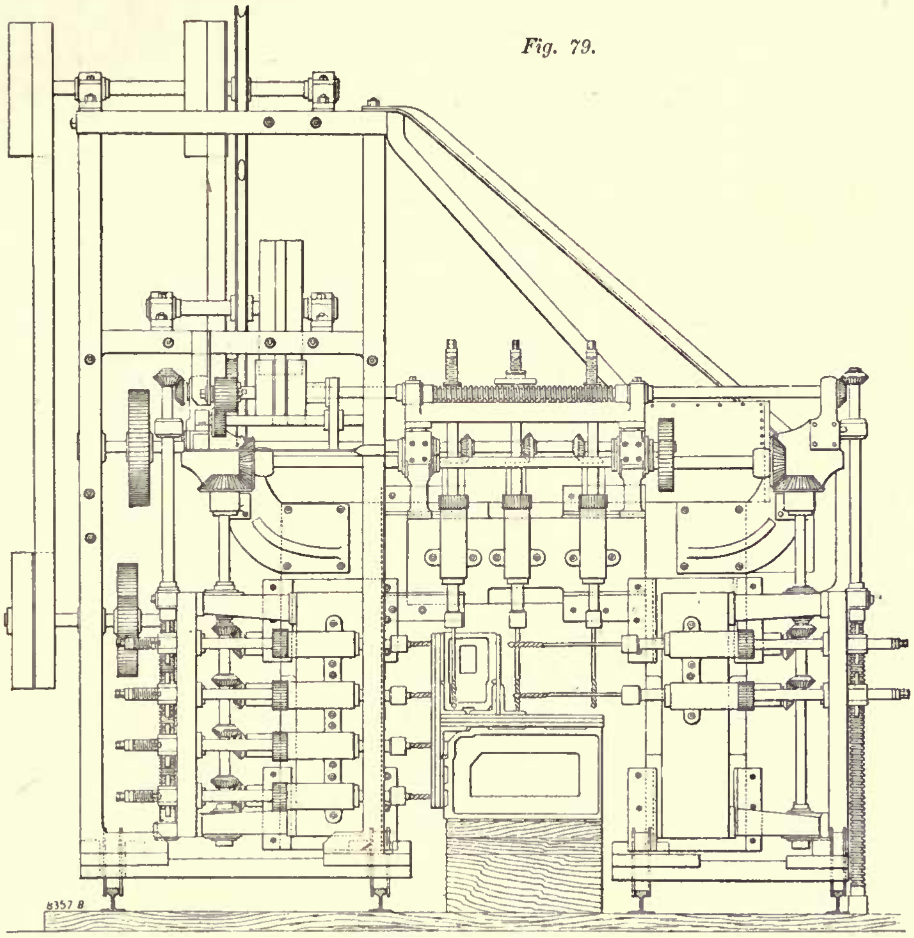
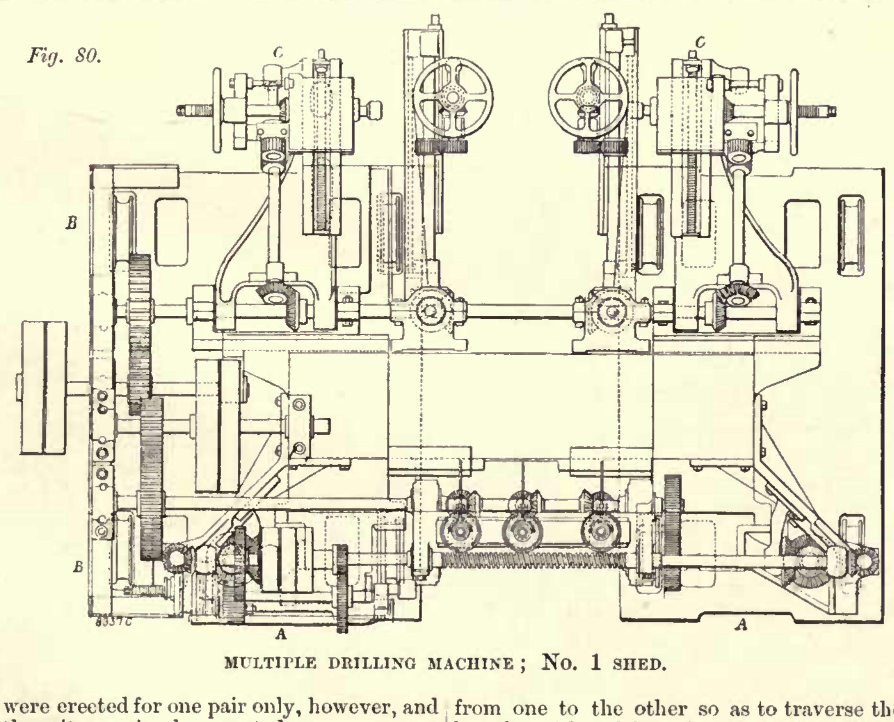


Fig. 80.



MULTIPLE DRILLING MACHINE; No. 1 SHED.

The work in both No. 1 and No. 2 sheds, and on the drill-roads, was carried on day and night, though the number of men was much greater during the day-time. The working hours were from 6 a.m. till 5.15 p.m., and from 5.45 p.m. until 5.45 a.m. for night shift. No deduction was made for meal hours during the night, the full twelve hours being paid for. When necessary the work in the field was also carried on during the night.

The total output of work from all these places has amounted to as much as 1800 tons in a month, which is a very large quantity when it is considered through how many hands every piece was required to pass before it could be called finished.

Bedplates.

The lower or fixed bedplates, in size about 37 ft. long by 17 ft. wide, are built up of five layers of plates, the lowest $\frac{3}{4}$ in. in thickness, the second $1\frac{1}{4}$ in., and the third and fourth 1 in., alternately laid longitudinally and transversely, to obtain distribution of fibre in all directions. The fifth layer consists simply of a band, 11 in. wide and $\frac{1}{2}$ in. thick, laid round the edges of the bedplate, partly as a stiffener, partly as a means of retaining the lubricating medium between the lower and upper bedplates. Immediately under the vertical column a recess is formed by cutting out of the two upper 1-in. plates a space varying in form, but in all cases for the purpose of admitting a keyplate of similar form, a portion of which is rivetted to and forms part of the upper bedplate.

The bedplate as above described was put together on a carefully-prepared bed in No. 1 shed, clamped and fastened down securely, and a traveller with several boring spindles passed over the whole of the plate, drilling all holes through the various thicknesses at once.

All holes were $1\frac{1}{8}$ in. in diameter, and countersunk both top and bottom. The forty-eight holes 3 in. in diameter for the holding-down bolts were drilled in the same place, but by a specially constructed tool described above, and the plate was then taken to pieces and stowed away until wanted.

As soon as the granite piers were ready for the reception of the bedplates they were put together at a height of about 4 ft. above the masonry, and supported for the time being on short pieces of bolts, coupled to the foundation bolts by long nuts and in other places by pieces of cast-iron piping of equal length. The rivetting machine was then placed at one end, and the rivetting commenced. (See Figs. 86 and 87.) The machine consisted of two strong box-plate girders, carried on two side-frames moving on wheels, and kept apart vertically a sufficient distance to admit the bedplate, with a rivetting cylinder attached to the upper and another to the lower girder. The cylinders could by screw movement be moved from one end of the girders to the other, and thus commanded the whole width of the bedplate, while for forward or backward movement the side-wheels had to be pinched. The two cylinders were turned on simultaneously by one valve. The cylinders were 12 in. in diameter, and the water pressure 1000 lb. per square inch. The pressure upon the rivet and the plates was, therefore, about 40 tons from each cylinder. The rivets had a countersunk head at one end, and flat snaps were used on both cylinders. The rivets were heated in an ordinary brick furnace placed on the pier, and brought to a full yellow heat. There were 3778 rivets in each of these bedplates, which gives for the area of 654 square feet about six rivets per square foot.

As soon as the machine had moved away a yard or so from the end of the plate, chippers were set to work to pare down the projecting piece on each rivet-head on the under side of the bedplate, in order to have this perfectly even and flush.

After the men got into the way of properly using the rivetting machine, these bedplates were rivetted up in twenty-eight hours, or 135 rivets struck per hour, which is very creditable work, considering the size of the rivets and that so much shifting of the machine and of the supports for the bedplate had to be done.

After all the rivet-heads had been chipped, the bedplate was lowered into its place by hydraulic rams. Two thicknesses of canvas, one laid in the length, the other in the breadth of the plate, both being well soaked in and painted over with red lead, were interposed between the cement bed described above (see granite piers) and the plate to

EDGE-PLANING MACHINE FOR LONG PLATES OF LATTICE GIRDERS; NO. 1 SHED.

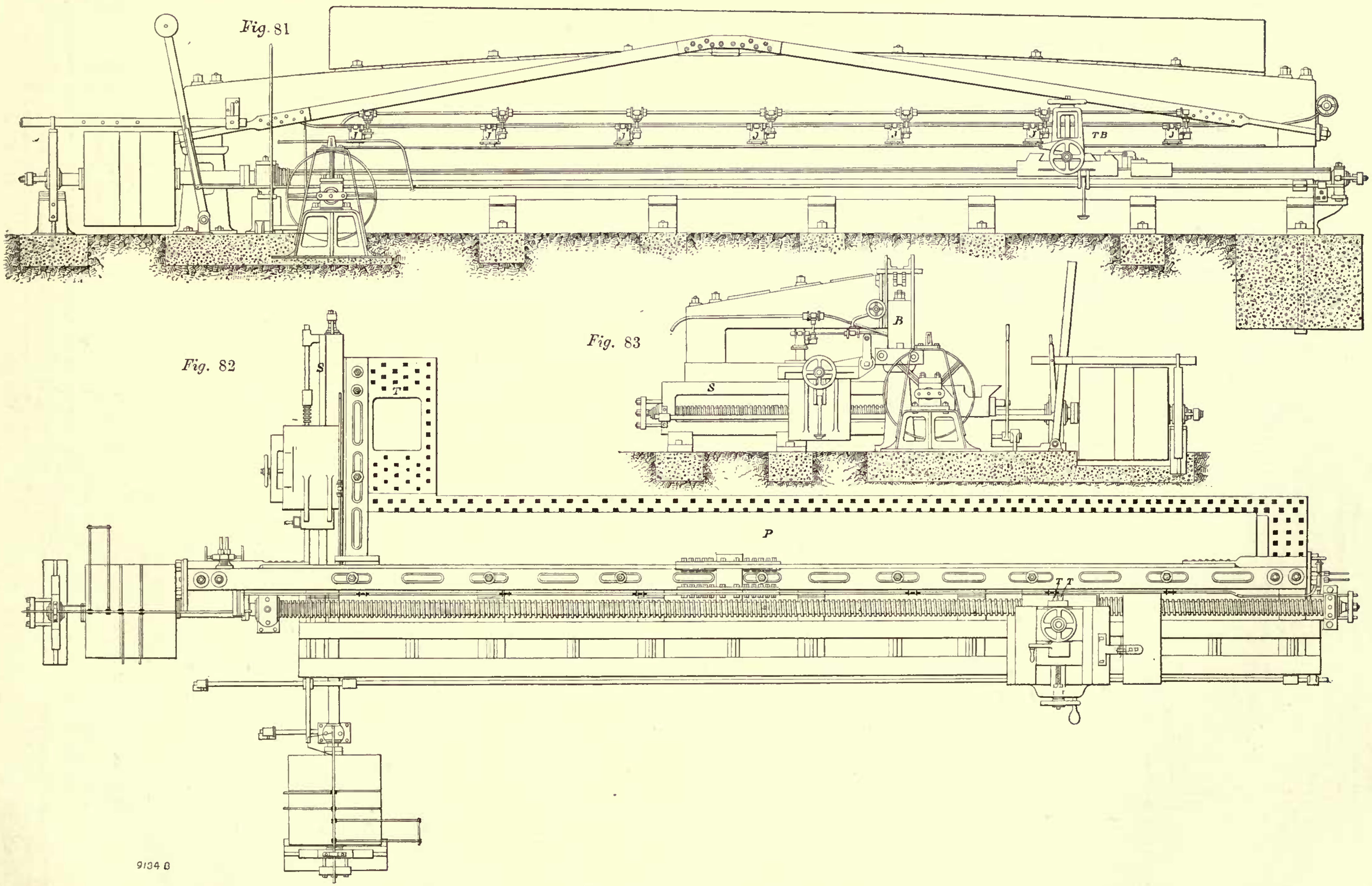


Fig. 81

Fig. 82

Fig. 83

make a water-tight joint. Nuts were then placed on the holding-down bolts, and screwed down hard with long spanners. As the bolts have no play in the 3-in. holes of this bedplate, the latter becomes thus an absolute fixture upon the pier. The weight of these bedplates is 44 tons each, except those in the fixed cantilevers, where it is 33 tons only.

The projecting parts of the rivet-heads on the upper side of this bedplate had now to be removed, and various means were devised to do this—rose bits, ordinary flat drills, and emery wheels being all tried in succession; but hand-work by chisel and hammer was in the end found to be cheapest.

The various forms given to the recesses in the lower bedplates and to the key-plates fixed to the upper bedplates are shown in the sketch. (See Fig. 88.) In the three piers already mentioned above as the fixed points, a plain circle is shown, and here the key-plate fits the recess exactly without any play. The lined spaces shown in the other piers give an indication of the amount of play between key and recess, and also the direction in which movement can take place.

Thus, in the remaining three piers on Inchgarvie, longitudinal movement alone can take place and a slight amount of circular movement round the centre of each individual pier. In the Queensferry north-west, and Fife south-west, these movements

are precisely the same as those on Inchgarvie, while in the Queensferry south-east and south-west, and the Fife north-east and north-west, both longitudinal and lateral movements are provided for. The former is for expansion and contraction between the fixed circular piers and the cantilever end piers, the latter for any lateral deflection in the same length due to wind-pressure acting at right angles, or nearly so. In the cantilever end piers lateral movement is prevented, but longitudinal movement provided for.

It will be noticed that the key-plates, with the exception of those belonging to the fixed cantilevers, are shown in three parts, an oblong centre-piece and two segments of a circle. Of these, the two segments are only 2 in. in thickness, and therefore simply fill up the recess in the lower bedplate, while yet, however, they admit and facilitate, as well as control, a circular movement round the centre. The central part, or oblong key-plate, is $2\frac{3}{4}$ in. in thickness, and enters therefore to the extent of $\frac{3}{4}$ in. into the upper bedplate, to which it is rivetted. This, however, is somewhat different in the three fixed piers, for here both the two segments and the rectangular centre-plate are all alike $2\frac{3}{4}$ in. in thickness, and the whole key-plate, 12 ft. in diameter, enters into the upper key-plate. The central piece is the only one attached by rivetting, the wings simply are laid loose into the recesses.

The square key-plates in the bedplates of the fixed cantilevers are fixed to the upper bedplate, and enter the lower bedplate to the extent of 1 in. only, the whole bedplate being much lighter than in the case of the free cantilevers.

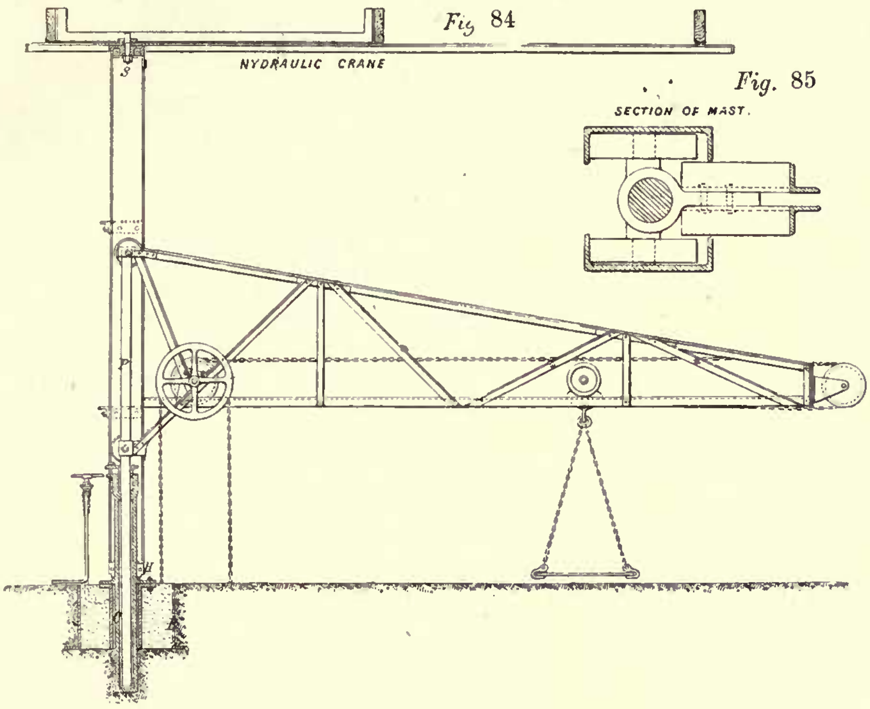
The upper bedplates form the under part or foot of the main junctions or skewbacks. These plates are, like the lower bedplates, built up of several layers of plates of varying thicknesses, according to position. The lowest course of plates, placed longitudinally, is $\frac{3}{4}$ in. in thickness, and in this is cut the recess which receives the key-plate of whatever shape it may be. The next course is laid transversely—$1\frac{1}{4}$ in. in thickness—and extends, like the first, over the whole area. The third course, laid longitudinally, again is $\frac{3}{4}$ in. in thickness, but extends only for about two-thirds of the area on the side next to the horizontal connecting bottom member. This plate also takes the attachments for the bottom booms of the horizontal cross bracing and the horizontal diagonal bracing. (See Fig. 91.) A further thickness of plates, as a fourth course, occurs in the case of the fixed piers, to make up for the enlarged recess in these, and this course is formed under the base of the vertical columns only.

These plates are stiffened by twelve girders of I section—about 11 in. deep, and running longitudinally—consisting of web-plates and four angles. The third and fifth girders on each side are omitted, the main webplates of the skewback taking their places. (See Fig. 90.) Transversely these girders are combined and stiffened by cell-plates, flanged on all four sides in a die. There are eleven rows of these, and upon them are set the main diaphragms, which reach from the bedplates to the crown of the skewbacks. The remaining spaces on each side of the inner webplates, and between these and the outer web-plates, are filled by similar diaphragms, and at the same distances apart.

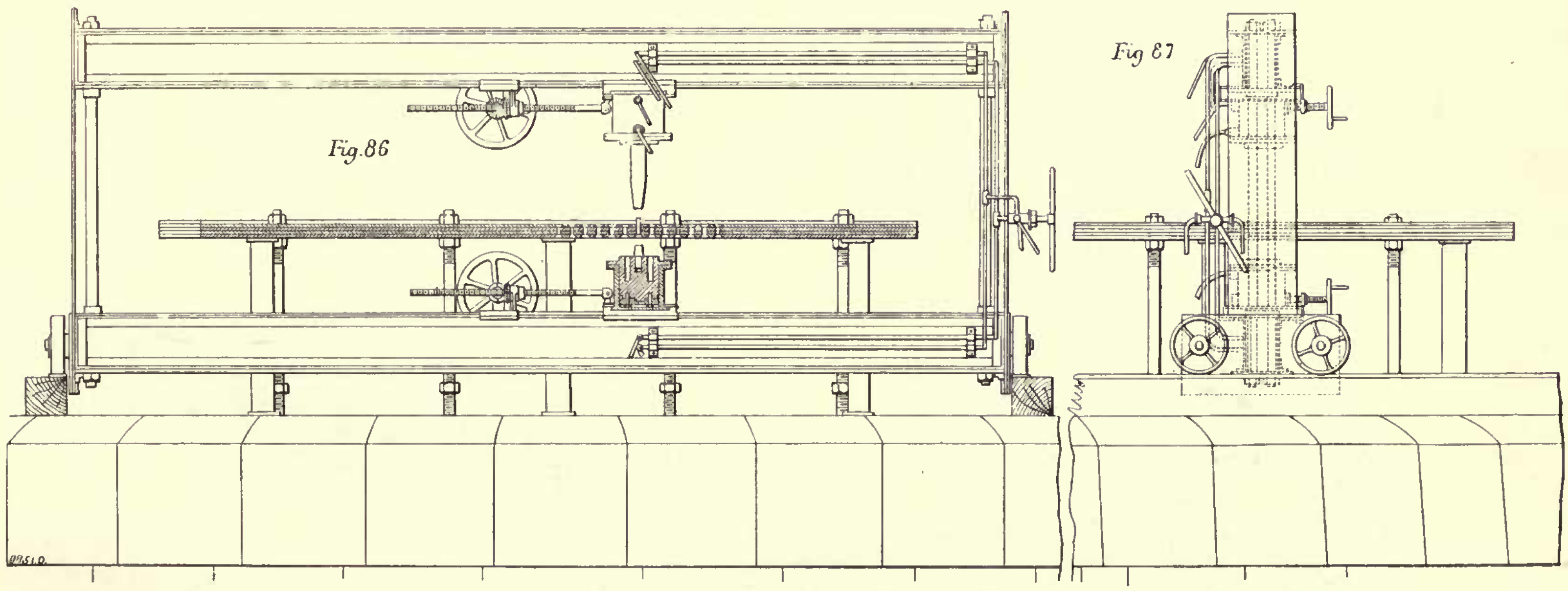
The sections and plans shown in Figs. 89 to 94 will fully explain these parts, which are of the utmost importance, because through them all the stresses thrown upon or against the structure, must pass on to the supports. The lower half of the skewback is square in form, the upper half for about two-thirds is rounded, the remainder being squared in order to receive the attachments of the top booms of bracing girders mentioned above. The inner main webs are $\frac{7}{8}$ in. thick on Fife and Queensferry and 1 in. thick on Inchgarvie, and these are carried through from end to end of the skewback at a distance of 3 ft. 6 in. to each side of the centre line. These plates form the main points of attachment for the diagonal struts and for the bottom members, both within the central towers and in the cantilevers. The outer webplates, 1 in. thick on Fife and Queensferry and $1\frac{1}{4}$ in. thick on Inchgarvie, receive the main thrust of the vertical columns, and are carried on each side into the bottom members by a change from the rectangular into the circular form. (See Figs. 92 and 93.) They are considerably stiffened in these parts by horizontal diaphragms and by doubling plates of great strength, and the skeleton work to which they are attached is gradually merged into the main beams of the regular section of the bottom members.

The attachments of the five lattice wind-bracing girders, although most ingeniously contrived, does not call for any special remark.

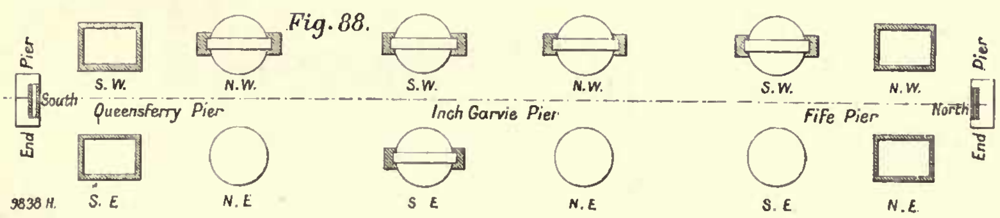
It will be noticed in connection with the skewbacks that the centre of the vertical columns does not coincide with the centre of the circular granite



HYDRAULIC CRANES.

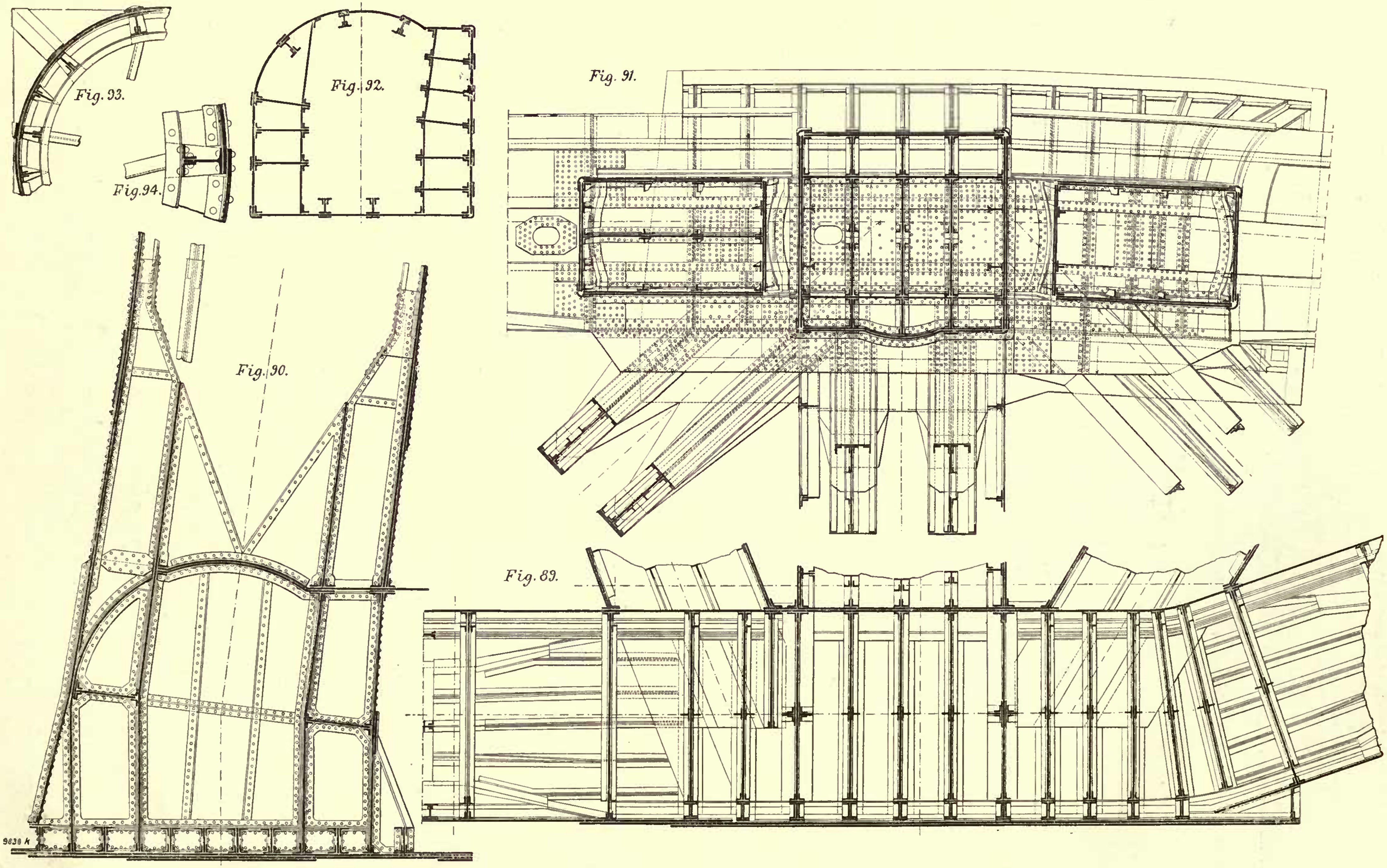


RIVETTING MACHINE ON PIERS FOR BEDPLATES.



ARRANGEMENT OF BEDPLATES ON GRANITE PIERS.

DETAILS OF SKEWBACKS OVER PIERS.



pier, but that it is set back 5 ft. to the inside of the pier, the centres between the vertical columns being, therefore, 10 ft. less than the distance between piers. This was done with a view to the better distribution of the downward stresses, which are greatest in the bottom members of the cantilevers; and as it was for structural reasons not practicable, or, at any rate, expedient, to bring the centres of the main compression members to one point, it was thought best to make the distribution as even as possible.

To return again to the upper bedplate. This was put together with all its longitudinal I girders and transverse cell-plates upon the pier, resting upon supports similar to those used for the lower bedplates. The same machine was used for rivetting the bottom portions of the plate, and all rivets were countersunk on the under side, while for the upper end a bent snap had to be used in order to get round the flanges of the girders and cell-plates. On the under side all projecting rivet-heads had to be removed as before. The key-plates were now placed in the recess of the lower plate to ascertain whether they fitted and had good

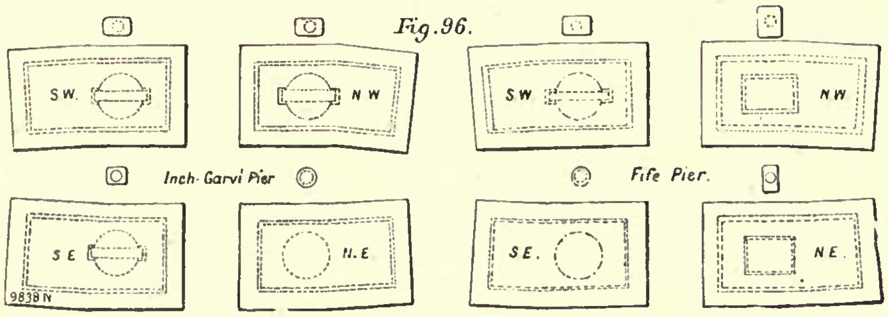
bearing all round; and after these were found to be satisfactory, the rectangular portion of the key-plate was raised up and rivetted to the upper bedplate. This was then lowered down into its place to see how it fitted, and whether all parts of the key were in proper contact. After thus lowering and raising it several times (a weight of about 57 tons), the surfaces were carefully cleaned and thick brown oil of a special character was poured into the key recess and on the whole area of the lower bedplate, and the upper bedplate lowered down upon it for the last time. Nothing else but oil was placed as lubricating medium between the two surfaces.

The movements described in connection with the keyplates require that a certain amount of play be given in the holes of the upper bedplates through which the holding-down bolts pass. The amount of play varied, of course, in the same manner as with the key-plates.

The lower bedplates being fixed and held down firmly by the bolts, it was necessary that the nuts should be screwed down upon them. These nuts, shown in Fig. 95, were therefore arranged with a long neck, circular in form, and with an enlarged head of hexagon form. The holes in the upper bedplate had to be therefore made of such size and shape that with the nuts screwed down tightly upon the lower bedplates, with a considerable stress upon the holding-down bolts, the upper bedplate could yet move in any desired direction without hindrance.

This was done by means of a washer of oblong form placed upon the carefully-levelled sides of the cells in the bedplates, which had bolts passing through them. The nuts were first put on and screwed down by means of a hydraulic spanner—that is, a heavy box spanner with a short lever on the top of it, to the end of which a hydraulic ram was applied with a given pressure. This assured an even stress to all the bolts. The distance between the side of the cell and the side of the head of the nut was then carefully callibered for each nut, and the washers made to that measurement, one-sixteenth of an inch being allowed for play. The sizes and shapes of the holes in the upper bedplates are shown by the diagram here given, the holes for Queensferry bedplates being, of course, the same as those for Fife, but in reversed position. (See Fig. 96.)

Fig. 96.

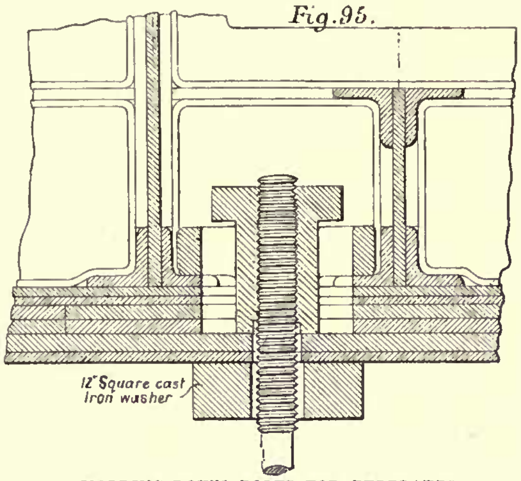


BEDPLATES ON INCHGARVIE AND FIFE PIERS.

The building of the skewbacks could now be proceeded with, and this was done in such manner that the work as erected was at once rivetted up by machine. The most difficult places to get to were the lower edges of the inner and outer webplates, with their double angles already rivetted to the bedplates. All the work in these cells which could not be done previous to the putting in of these plates had to be done by small hydraulic rivetters. These were simply cylindrical rams of 4 in. to 6 in. diameter, and in length from 6 in. to 10 in., and these were worked by a pressure of 3 tons per square inch. The cylinders were placed to either side of the rivet to be struck, facing each other, and backed by hardwood packings against the sides of the cells, and the pressure water was supplied to them through small copper pipes about $\frac{3}{16}$ in. in bore. The rivets were heated on the outside, and passed through holes in the webplates; one cylinder was set against the rivet-head, and the other then closed upon the free end, and formed a flat head, the hole on that side being somewhat countersunk. To produce the 3 tons per square inch pressure, a multiplier was used, consisting of an 11-in. ram, which was acted upon by an ordinary accumulator pressure of 1000 lb. per square inch, and which had at its end another ram attached, 4 in. in diameter, which was forced into a cylinder already charged with 1000 lb. pressure water. The 4-in. ram forced the water to a small accumulator, loaded to produce a pressure of 3 tons per square inch. It needs no saying that this was a tedious kind of work, and took a long time to accomplish. On many days not more than half a dozen rivets were done—at no time more than about a hundred in the twelve hours, and the average would not probably amount to more than twenty-five per day.

Meanwhile staging had been erected between the piers on trestles of certain height, upon which were put together the horizontal tubes connecting the skewbacks and the cross-girders and diagonal girders. All these were now connected to the skewbacks, and preparations made to rivet them up. All the erection of the lower portions of the central towers was done by 3-ton or 5-ton steam derrick cranes placed on platforms at some height from the deck and in convenient position to pick the material off the bogies and at once place it in position. For the rivetting of the latticed girders the ordinary fixed or jointed machines were used, which are extremely simple in their construction and their action. (See Figs. 97, 98, 99, 100, the three first representing fixed machines, the last a jointed machine.) It depended entirely upon the places where rivets had to be struck whether one kind of machine or the other was used; but the direct-acting machine was surer in its action, because the double lever arrangement was apt to twist, and thereby bend the unclosed portion of the rivet before the latter was properly staved. Of course the longer the arms the greater becomes this tendency, and as some of the jointed machines had to be used with the arms fully 4 ft. 6 in. in length, great care had to be exercised to get good work done.

Fig. 95.



HOLDING-DOWN BOLTS FOR BEDPLATES.

The horizontal tubes, built up of heavy plates $1\frac{1}{4}$ in. thick, required a special machine for rivetting, and as this machine is the same, or at all events typical of others, which were used for the rivetting of the bottom members, the vertical columns and the diagonal struts in the central towers, a brief description will not be amiss.

In the main it consisted of two circular girders, the inside diameter being about 1 ft. larger than the outside diameter of the tube. They were placed some 24 ft. apart and tightly wedged by hardwood blocks all round the tube. A box girder of a strong section, and about 25 ft. long was placed upon the ring girders in such manner that it could be pushed completely round the tube, and for this purpose hydraulic rams, one at each end were attached in such a manner that they could be fleeted forward or backward as desired. Upon the box girder a cylinder was placed facing the tube, being connected to a saddle which was capable of sliding from one end of the girder to the other. The saddle was worked by a ratchet and pinion, the latter working upon a rack which ran along the whole length of the girder. Finer adjustment could be given by two screws and handwheels on the saddle, like that of a lathe. By this means the centre of the cylinder could be brought opposite any point of the surface of the tube within the length of the girder. On the inside of the tube a mandrel or central hollow shaft was formed of the same length as the outside girder, and this was supported at both ends by frames fixed and wedged to the skeleton frame of the tube. On this mandrel a toothed rack was fixed, and a saddle worked by ratchet and pinion could move from end to end. Upon this saddle a cylinder of the same size as the outside one was placed with a long snap or dolly reaching to the plates. The supply of pressure water was so arranged that both cylinders would be turned on simultaneously, but by means of a check valve placed upon the outside supply pipe, the motion of the outside ram was slightly retarded. The girder outside was now placed in line with a row of rivets in the tube, and the inside cylinder was set opposite the same row. The rivets were heated in small furnaces or forges on the inside and heated to a good yellow heat. As soon as a rivet was put into place the inside dolly was set against it, the outside ram being also set down, a tap given to indicate that all was ready, the pressure was turned on, and the rivet closed. The two cylinders were then moved forward, one pitch to the next hole and so on. When a whole row extending over about 18 ft. in length had been done, the girder was raised or lowered as the case might be, to the next row, and this continued until the whole section of the tube was rivetted. The machine was then moved 18 ft. forward and the process repeated. No drawing of these rivetting machines is given here, but a machine similar in construction, and used for rivetting the vertical columns, is shown further on.

Between 600 and 700 rivets could be put in by this machine per day, all rivets here being $1\frac{1}{8}$ in. in diameter. Only the rivets passing through the thick outside plates and beams were done by the machine. Of these there were about 1550 in each section rivetted, or nearly 100 per foot run. The other rivets, in diaphragms and beam-covers, were done by hand. The least number of hands to work this machine were three men outside and two men and a boy inside, with a lad for heating the rivets and a boy to carry them.

The members of entirely circular form were the vertical columns, the horizontal tubes or bottom members between skewbacks, and the bottom members in cantilevers from the skewback to the end of bay 4. In design and in construction they were all the same—differing only in diameter—in the breadth and thickness of the plates, and in the depth and strength of the longitudinal beams. All plates are made, except in special places or for closing lengths, of a uniform length of 16 ft., and the tube is formed of ten plates, lap-jointed, and therefore consisting of five outer and five inner plates. All plates break joint at 8 ft., or half length, with an absolutely close butt, and the butts are covered inside and outside by plate-covers. The lap-joints are covered on the inside by ten continuous girders of T section, the T head being rivetted in with the lap-joint, and two continuous angles are rivetted to the other end of the web, thus making the girder of double T or H section. (See Figs. 68, 73, and 94.) The beams are made in lengths of about double that of the plates, and break joint in different places, and all their joints are covered both in the webs and flanges. At every butt—that is, every 8 ft.—is placed a circular girder or diaphragm, which consists of ten wings placed between the beams and rivetted to the shell, the wings projecting beyond the beams to the extent of about 3 in. An angle-iron ring running right round takes up all the wings to its web, while its heel is rivetted to each of the beams in succession, and thus combines the whole into a stiffening girder. At considerable distances apart, heavy plate-diaphragms are inserted which only leave a manhole in the centre to pass through. All these diaphragms are primarily for the purpose of preserving the true circular form of the tubes, and to prevent flattening; and it is a curious fact that the stiffest of these tubes, although bolted together in the most careful manner flat-

tened before rivetting as much as 3 in., and had to be constantly strutted with timbers to keep it in form.

The plates forming the shell of the vertical columns varied in thickness in the case of the Fife and Queensferry central towers, from $\frac{1}{2}$ in. at bottom to $\frac{3}{8}$ in. at top; and, in the case of Inchgarvie, from $\frac{5}{8}$ in. at bottom to $\frac{7}{16}$ in. at top. The beams decreased in strength proportionately.

The diagonal columns or struts in central towers are of different shape, namely, circular top and bottom, but flattened on both sides in order to facilitate their intersection with each other and their entering into junctions top and bottom, where they are gradually changed into rectangular section. It has been pointed out in the general description of the bridge, that the effects of the live load upon the Inchgarvie cantilever are different from those in the Fife and Queensferry piers. The diagonal struts in the former case are therefore very much stronger than in the latter. The bottom and top plates are $1\frac{1}{4}$ in. in thickness, while the corner and side plates are 1 in. thick. The intersection of these two struts at centre of the tower is very heavy, some 80 tons of metal being massed therein. The inside beams are of corresponding strength. These diagonal columns were rivetted in the case of Inchgarvie from top to bottom by a special machine of similar design as that for the vertical columns, but more difficult to work on account of the angle at which the machine was placed.

Meanwhile, steam derrick cranes were erected on platforms raised some 30 ft. to 40 ft. above deck, commanding the whole of the skewbacks, and these were now built with portions of the diagonal struts, the vertical columns and the struts 1 in cantilevers, to as great a height as could be reached by means of these cranes. All this work was put together as carefully as possible, the larger number of holes being drifted up, but it was only bolted together pending the necessary checks and corrections being made by means of theodolites. This setting out was a work of no small difficulty, seeing that the members had to be set, not only to an inclination towards the point of intersection, but had at the same time to follow the uniform batter of the vertical columns, and had therefore a strong tendency to lean to the centre of the tower.

So soon as the vertical columns and struts had been built to a height of about 50 ft. above deck, to which, in the case of Inchgarvie, had to be added the central ties, preparations were made for the construction of the lifting platforms, by means of which the central towers were raised to their full height.

A staging, reaching on each side, north and south, from column to column, about 25 ft. in width, was raised from the deck to a height of about 38 ft. above the level of the staging, and upon this a pair of longitudinal girders were built. These girders were about 190 ft. long in the case of Fife and Queensferry, and 350 ft. long in the case of Inchgarvie. (See Figs. 101 and 102.) There were four girders—one to each side of the vertical columns—placed 18 ft. 6 in. apart, with angle cross bracings top and bottom, and diagonal bracing between top booms on one side, and bottom booms on the other side, alternately. The main booms, D D, Fig. 101, and most of the vertical angle bracing, were permanent work, being, in fact, the booms belonging to a portion of ties 1 in the cantilevers borrowed for the occasion. This platform and all its details are shown in a large number of the text illustrations as well as plates.

During the time these girders were being put together, a strong box girder C C was built on a staging between vertical columns east and west, which girder passed through openings left in both columns, and projecting outside of each, to the extent of about 4 ft. or 5 ft. For this purpose one plate was left out on each side of the vertical columns during the time the girder passed aloft. This girder in its turn was supported upon a slide-block inside the vertical column, which block was attached to a cross-girder B B. This cross-girder was of double box section, all in plate, and in its turn was supported by a number of pins about $1\frac{3}{8}$ in. in diameter, which passed through girder and through holes drilled for the purpose in four of the **H** beams of the vertical columns. Immediately below this box girder, and at a distance of about 1 ft. from it, was a second box girder of the same dimensions A A, and held up in the same manner by a number of pins. Upon the lower girder was placed, on a rocking underside, a hydraulic ram G G 14 in.

PORTABLE HYDRAULIC RIVETTERS.

Fig. 97 *Fig.* 98

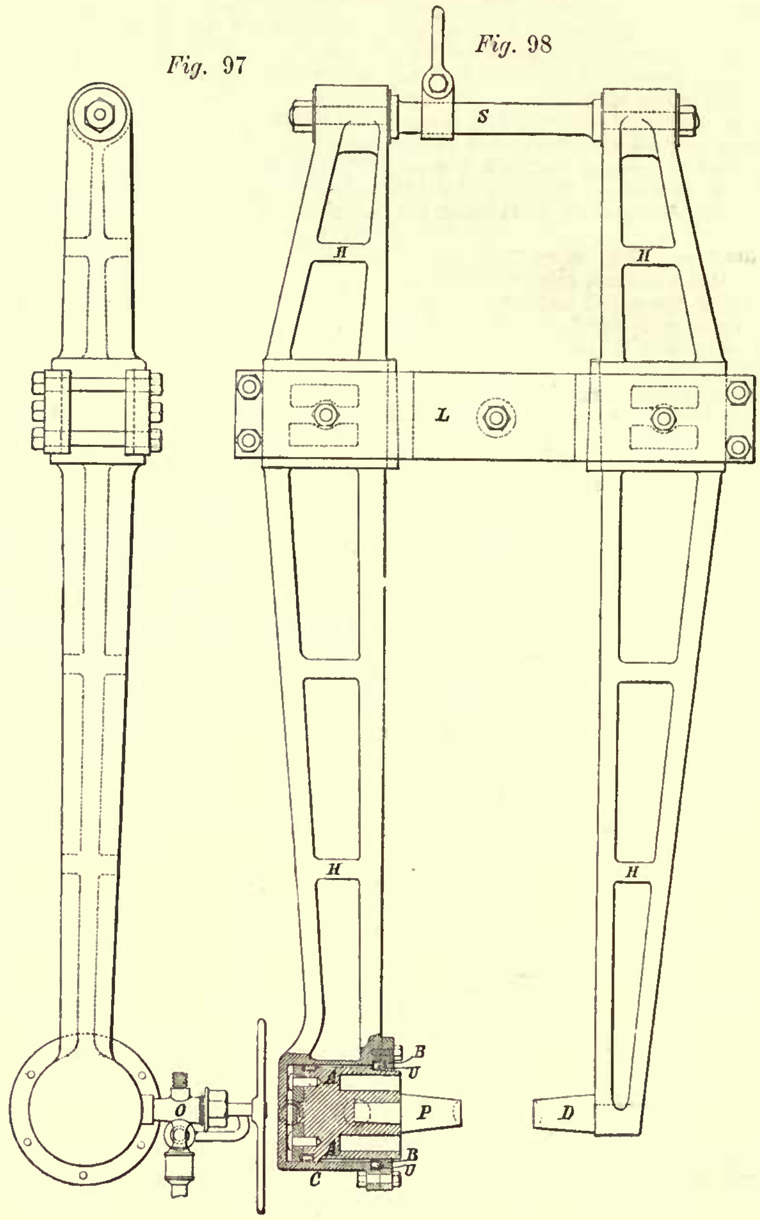
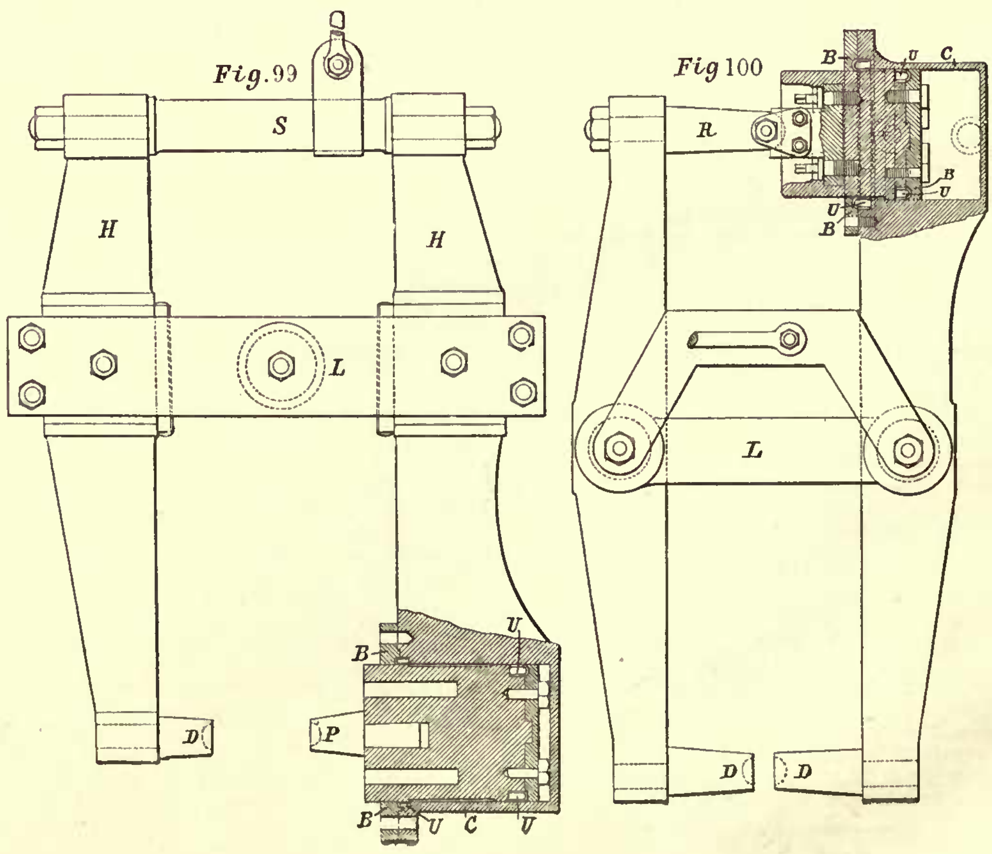


Fig. 99 *Fig* 100



in diameter, with a stroke of a little over 12 in., the cylinder and ram passing through the upper box girder. The head of the ram acted by means of a swivelling cap immediately upon the cross-girder CC passing from column to column. The working of these girders and rams was as follows:—The lower box girder was held by a sufficient number of pins to carry the total weight placed upon it.

As soon as a small amount of pressure water was allowed to enter the ram, the latter lifted the cross-girder C, and with it the box girder B, to a small extent. The pins could then be withdrawn from the girder B, and the girder lifted 6 in. or 12 in., as the case might be. The pins were then driven through the sides of the girder B into holes newly exposed, and the beams and the weight let down upon that girder. The pressure was then allowed to pass on the top of the ram, and the cylinder was drawn up to the ram, bringing with it the lower box girder A. every few feet of lifting to the extent of the batter of the vertical tubes, which is 1 in $7\frac{1}{2}$ about. (See Plate IX.)

With every few feet of lift these platforms had to be pushed together, which was done by hydraulic rams also, and this accounts for the number of slide-blocks mentioned above.

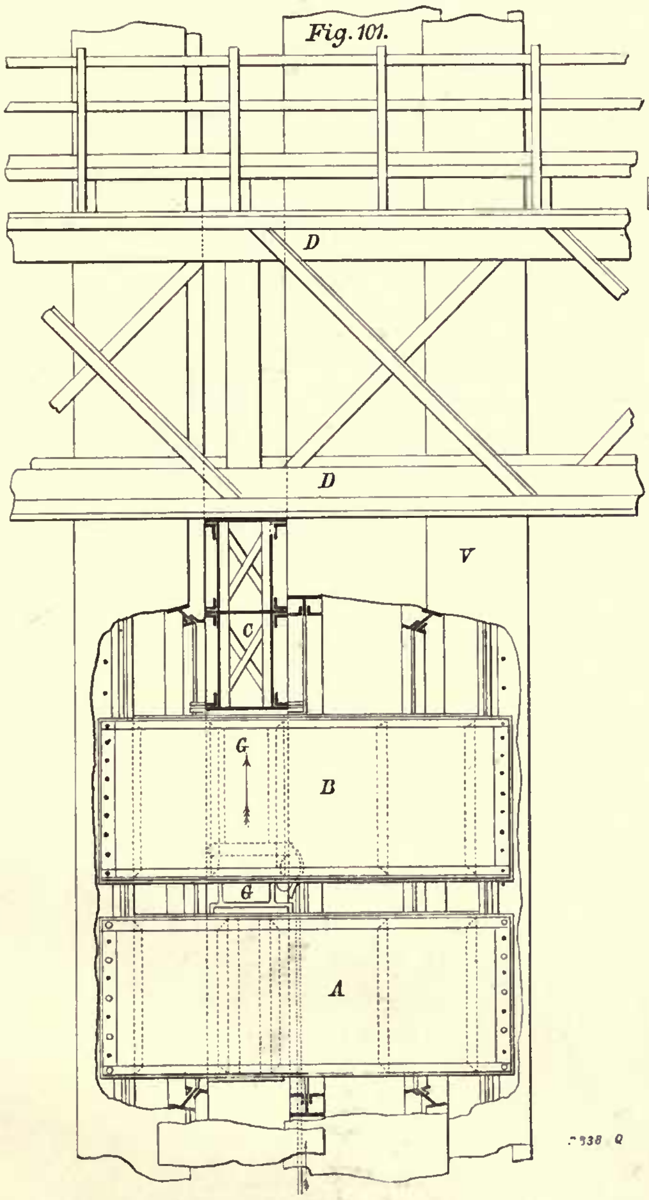
The ordinary routine in lifting was as follows:

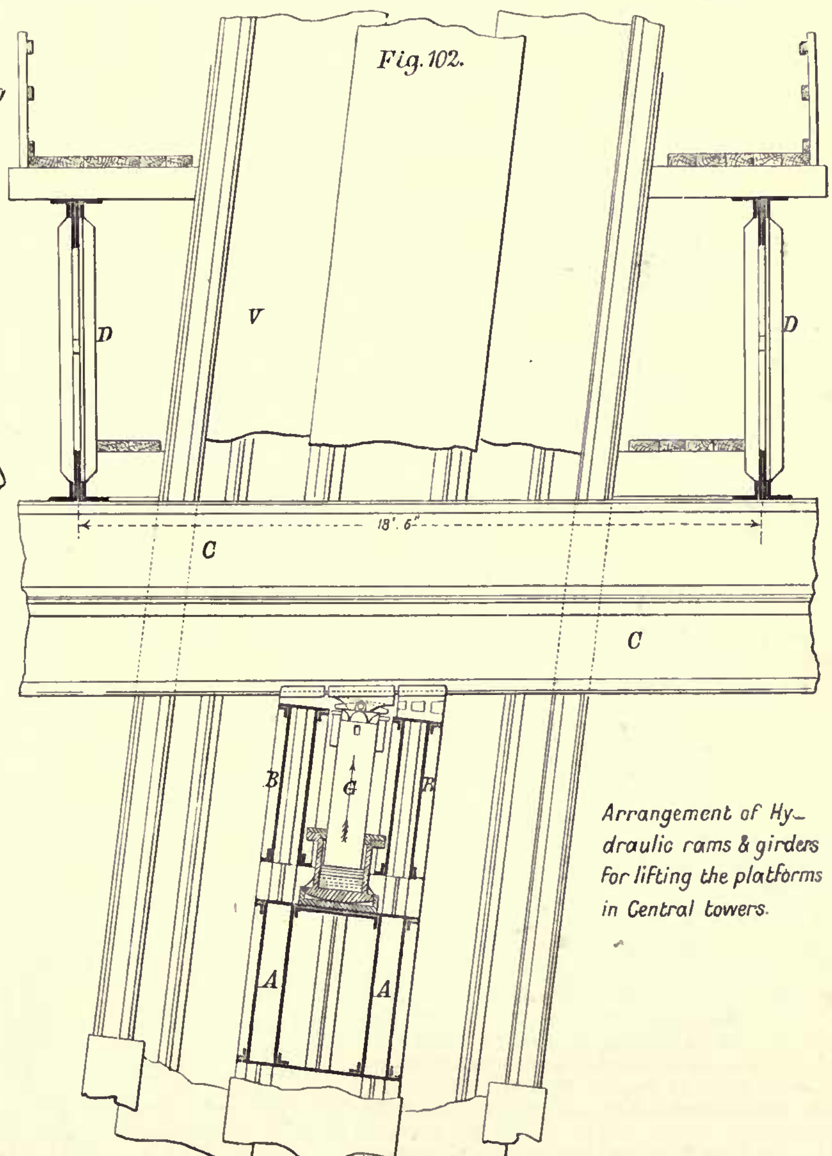
From a level position of the platforms the cross-girder in the north or south columns was lifted first 6 in; next the other end was lifted 1 ft.; then the opposite end 1 ft.; and so on until sixteen lifts had been made, when a last lift of 6 in. at the end which commenced the lifting made the platform level again.

When the platforms had in the first instance been lifted to a sufficient height, the rivetting cages were suspended from the under side of the platforms, and in subsequent lifts they were always

On the inside of the platforms at each end were hoists worked by wire ropes from winches placed on deck, and all plates, beams, and other material was brought up by means of these hoists and distributed over the platforms. (See Figs. 104 and 105.) Two-ton and 3-ton derrick hand cranes were found the most handy for the erection of the different members, but a traveller, or Goliath, worked by hydraulic power, was also used.

When a lift had first been made, the first work, as a rule, was to put in the two closing plates to each column which had been left out to allow for the passage of the cross girders. The inner part of the rivetting machine was then drawn up, the whole machine fixed, and rivetting was at once commenced; while above the platform a section was added to the vertical tubes and the diagonal struts. The platform on Inchgarvie being of so much greater length, and weighing fully 700 tons,





HYDRAULIC RAMS AND GIRDERS FOR LIFTING PLATFORMS IN CENTRAL TOWERS.

When the holes in girder and beams had come opposite, the pins were driven in, and the same process could be gone over again.

The arrangement as just described was placed in each of the four vertical columns, and in the case of Inchgarvie into the central ties as well, thus giving six points of support there, instead of four. The longitudinal girders were now placed upon slides on the top of the cross-girders passing from side to side, and the tops of the girders covered over with cross-timbers, and decked with planking 3 in. thick. Thus there were two platforms about 25 ft. wide by 200 ft. long, or 350 ft. long in the case of Inchgarvie, embracing completely and projecting to some distance beyond the vertical columns. Figs. 103, 104, and 105 show various positions and details of platforms.

At the starting-point just above the skewbacks these platforms were some 110 ft. apart, centre to centre, approaching each other, of course, with drawn up with the platforms. (See Plate IX., rivetting cages on Inchgarvie.) This cage simply consisted of a stout circular wire cylinder being placed round a rivetting machine, similar in construction to the one described for the horizontal tubes, but hung vertically. Inside this cage the men worked with perfect safety as regards falling themselves or dropping things down on those working below. (See Figs. 106 and 107.)

The portions of the rivetting machine inside the vertical column were not drawn up by the lifting of the platform, but were lifted separately subsequently.

The length of the plates in the vertical columns being 16 ft., the lifts of the platforms were of the same length.

The vertical columns were always built above the platforms to any height which could be reached with the cranes or other means at disposal, while the diagonal struts were at times built above, at times below the platforms.

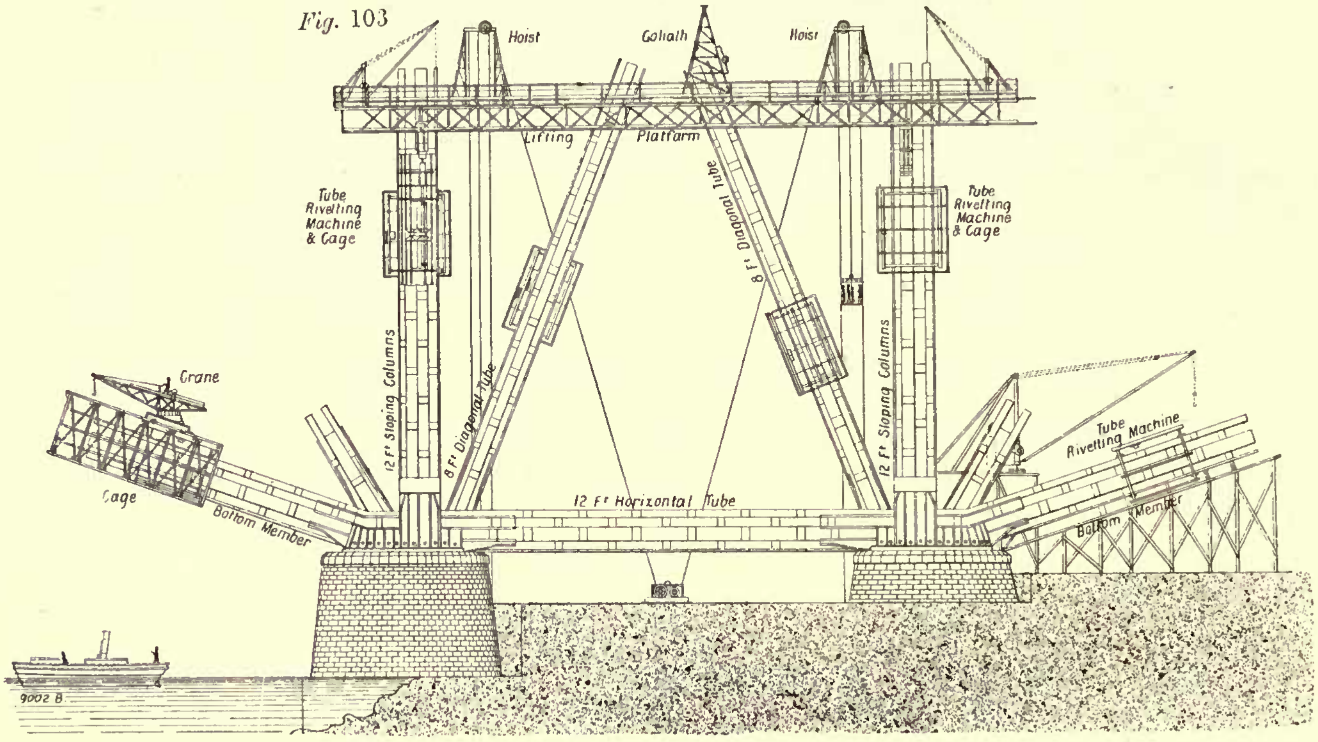
had to be provided with two additional supports, and these, of course, were carried upward the same as the vertical columns.

The water pressure for lifting was supplied by a special set of pumps which produced a pressure of 35 cwt. to the square inch. No accumulator was used, but the pumps simply forced up the rams gradually. Under this great pressure the cup-leathers in the hydraulic rams and the leather washers in the pipe-joints, frequently gave way and caused much delay. Frosty weather also did a great deal in the way of freezing pipes to hinder the work, but after once the men had got into the way of working the plant, things went more smoothly. The first lift of the Inchgarvie platform took, with one thing and another, nearly eighteen days in the months of January and February, 1887; while the last lift, on the 9th of August of the same year, was accomplished in five hours. With the batter which the vertical columns and other side members

have towards each other, it is easy to understand that, independent of any weight which was imposed on them, they would be liable to deviate from their true position. It was, therefore, necessary from time to time, that is every 30 ft. or 40 ft., to secure the members by the interposition of temporary struts or ties either in the shape of lattice girders or of timber balks, and even timber trusses. Thus, after two lifts had been made with the platforms, the diagonal struts in the central easy to handle. The men also had become so familiar with the work that they knew exactly what was required, and made little account of the height at which the platforms had now arrived, namely, some 200 ft.

At the next halt a great deal of work required to be done, namely, to build in the crossing of the diagonal struts in the centre of the pier. This for obvious reasons could not very well be done above the platform, but some 20 ft. below. In the case of tower, and a new start upwards could be made from a fresh fixed base. At this stage a prodigious amount of work was done, immense quantities of material were drawn up the hoist and distributed on the top of the platforms where the platers, working on tall ladders, bolted up beams and plates often 25 ft. above the platforms. Between the top of the platform and the bottom, men were at work removing and replacing temporary bracing, which came in the way of the diagonal struts as they were built

Fig. 103



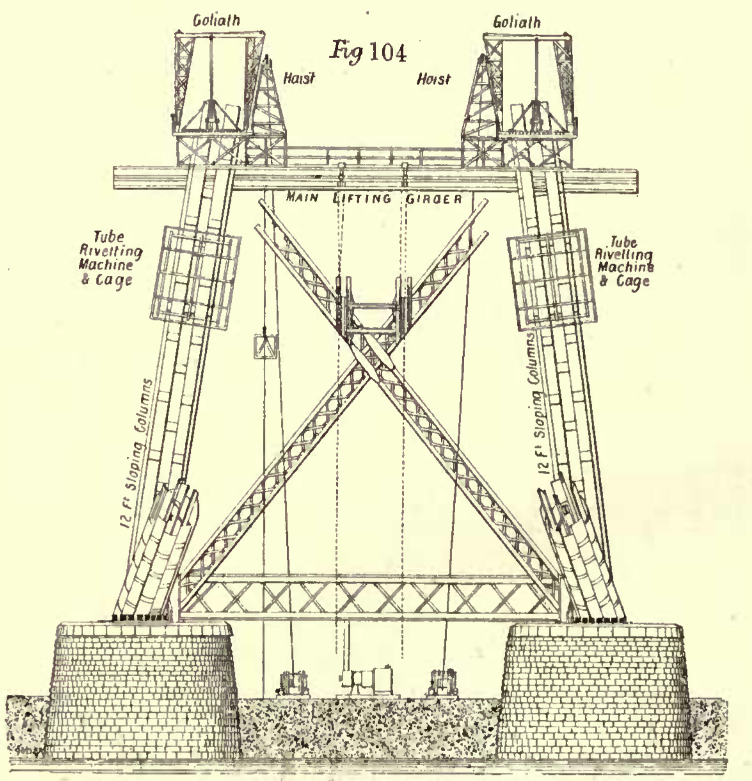
towers had not only deflected downwards by their own weight, but had also deflected towards the centre line of the bridge. It was not possible to go any further without putting them right, and this was done by girders placed both longitudinally and transversely between the struts, and using hydraulic rams to push them apart. In the case of the vertical columns the same difficulties arose, and here strong timber struts were interposed. For the same reason, the first diagonal bracing between these columns was kept up as close as possible to the platform. (See Plate X.)

Nor was this the only matter requiring care, for although these columns might be kept the proper distance apart from each other, yet might they also both deflect in one direction, be this east or west, north or south. With the heavy platforms carried on these comparatively unconnected members, a strong wind from one side or the other could produce serious distortions and deflections, and the rivetting up of the vertical columns following so close upon the rise of the platforms, made them so stiff that it was not easy to deal with them. In checking the columns, reference was always made to the centre line of the bridge, which was thrown upon the cross girder which carried the platforms, and measurement from this centre was taken to each side. That side which deviated least was first dealt with and pulled or pushed to the right position ; there it was held by wire rope ties or timber struts, and the other corrected subsequently. This cross-girder itself was used for pushing the columns apart or in, one side being fixed for the time and the other left loose.

The first thorough correction was made at the top of the first vertical wind-bracing between the columns, where a solid plate girder passes right across, which carries the internal viaduct girders. This is shown in Plate X. The large gussets were fixed to the columns, and the booms of the latticed girders brought up to them. But the gussets were not yet drilled, and only after the position of one column had been ascertained and corrected, these holes were drilled, and the corner booms fixed. A fixed point being thus obtained, the other column was either pushed out or drawn in as the case might be, and the booms fixed in the same manner.

By this time the platforms had already approached each other to half the original distance, and all the temporary girders became much shorter and more

Fig 104



ERECTION OF TOWERS.

Inchgarvie this crossing contains 80 tons of steel on each side, and at the crossing of the vertical tie at centre, and the horizontal bracing occurs at the same point, a very intricate piece of work required to be done.

Here the vertical columns could be corrected for position north and south by means of the horizontal bracing which runs longitudinally from one vertical column to another, intersecting the crossing of the diagonal struts. A pair of horizontal bracings are also placed here between the four columns as shown in Fig. 4, Plate III. A strong framework, similar to the one immediately above the circular granite piers, thus closed the lower half of the central up. Inside the columns, the hydraulic men were busy preparing for the next lift and examining the caps, leathers, and pipe joints. Below these in the cages and inside the tubes, the gangs of machine rivetters vied with each other which could get done the quickest, a premium being paid to the squad that had done its section first. Again, below the cages, men were replacing diaphragms and other details of the structure which had been removed to allow the lifting girders to pass, and still lower down, squads of hand-rivetters were rivetting up beams and diaphragms, and putting in such rivets as the machine had not been able to do. Besides these a host of other men—carpenters to put up

stages, gangways, timber stiffeners, floors, and all sorts of things; men attending to the rivet furnaces and trying to keep the machines going which put in their eighty to ninety rivets every hour, electric lightmen shifting lamps, putting in carbons and fixing fresh cables, and finally the hundred and one men who never seem to do anything, and yet cannot somehow be spared.

At last the tops of the platforms have reached their final position; and they can go no further, although the superstructure itself has to rise some 20 ft. more. (See Plate XII. and Fig. 108.) The two platforms by now have come so close together that the inner hoist-frame on one side had to be removed previous to the last lift. The long box girder now projects a long way outside each column, and stands quite clear above them; the whole platform looks as if a heavy gust of wind would lift it up and throw it over the side. The last length of beams and the closing lengths of the plates require to be measured before they can be cut to length. Once more the columns are carefully set to the centre line of the bridge and to north and south, and the levels of all the beams in the columns taken.

While these are being got ready, the gap of about 9 ft. between the two platforms is covered over, and only one platform exists now of more than double width.

The longitudinal platform girders were stiffened and trussed by link chains stretched from support to support. These chains were portions of the Hammersmith Suspension Bridge, bought up by the contractors, and largely made use of here in various ways. But the workmen would not consent to use the whole title due to them, for some of them called them Hammer links, and others called them Smith's links; but it required a Cockney by birth or adoption to get the combination.

These links were passed under double timbers, right under the two girders of each platform, and an initial stress was put upon them by interposing hydraulic cylinders between the timbers and bottom booms of girders, and filling the space made with hardwood blocks.

Blocks were now laid down on the top of the platform in the centre line of the top members, and the vertical webs of the bottom booms, the flange angles of the same laid down, and so soon as the top junctions were somewhat advanced, they were connected up at each end. The object was to relieve the platforms as soon as possible of any weight from the top members. The vertical bracings were then put on, and in these the webs of the top booms placed. The girders could now carry themselves, and rivetting was commenced as soon as the top junctions had been fixed and securely joined to the vertical columns. As there was a great deal of work to do upon these top junctions, they were completely surrounded by timber frames covered with boards, and provided with windows and a large number of electric lamps. Thus protected the work could be carried on day and night, and it was necessary, for every beam and every plate had to have its correct measurement and shape taken before it could be made. The ends of the diagonal struts, changing from a flattened round into a square, had to be templated in every plate and beam to make an exact fit. It will give an idea of the magnitude of the work when it is stated that these wooden buildings, of which there are four to a pier, erected at a height of 360 ft. above the water, were about 24 ft. square and fully 35 ft. high, with three floors at different heights.

The top junctions, although not of such importance as the skewbacks, are yet fully worthy of more than a passing remark. (See Figs. 109 to 115.) Here are united two tubular members—the vertical column and the diagonal strut—and five latticed members—the top member in the centre tower, the top member in the cantilever, the first inclined tie in the same, the highest of the four wind-bracings between columns, and the horizontal cross-girder between top junctions (the two latter not shown in the engravings).

The main strength of this junction lies in a number of very large webplates carried on each side of the centre in direct continuation of the webs of the top members. Inside these are the starting-plates, or horns, as they were popularly called, of the diagonal struts, and outside them those of the first inclined tie in bay 1 of the cantilever. Diaphragms, supported by stiff beams with a gradual change from round to square, connect it with the vertical column. The flanges of the top booms of the top members are carried right through, but the flanges of the bottom booms are replaced by extra plates and heavy angles. Most of the rivetting of the main webs was done by ordinary hydraulic rivetters, but a large number inside the cells, by small rivetters at the 3-ton pressure of similar construction as those used in the cells of the skewbacks. The top junction is shown in Figs. 109 and 110 in elevation and plan, and requires no further explanation. The rivetting of the top member between vertical columns was now pushed on as much as possible, and, as soon as completed, the working platform was transferred to the very top of these girders, and the removal of platform girders and all hydraulic lifting gear, commenced. This was all the more necessary since it will be remembered the platform girders were made out of portions of the first inclined tie of the cantilevers, and was now at once required to fill its proper place in the structure. Many of the plates and illustrations show details in connection with the lifting platforms and the work carried on upon them, but the space here is not sufficient to enter into description of them all.

The removal of these platform girders, many hundred tons in weight, with all the odds and ends of a working platform upon them, was a work which caused no little anxiety; for upon nearly every portion of the structure below, work was carried on by scores of men to whom the fall of a small bolt or nut from that height might cause danger to life or limb. The year in which the central towers were erected shows the greatest number of fatal accidents in any one year, namely, 17, while the average over the seven years is only 9.

Fig. 105

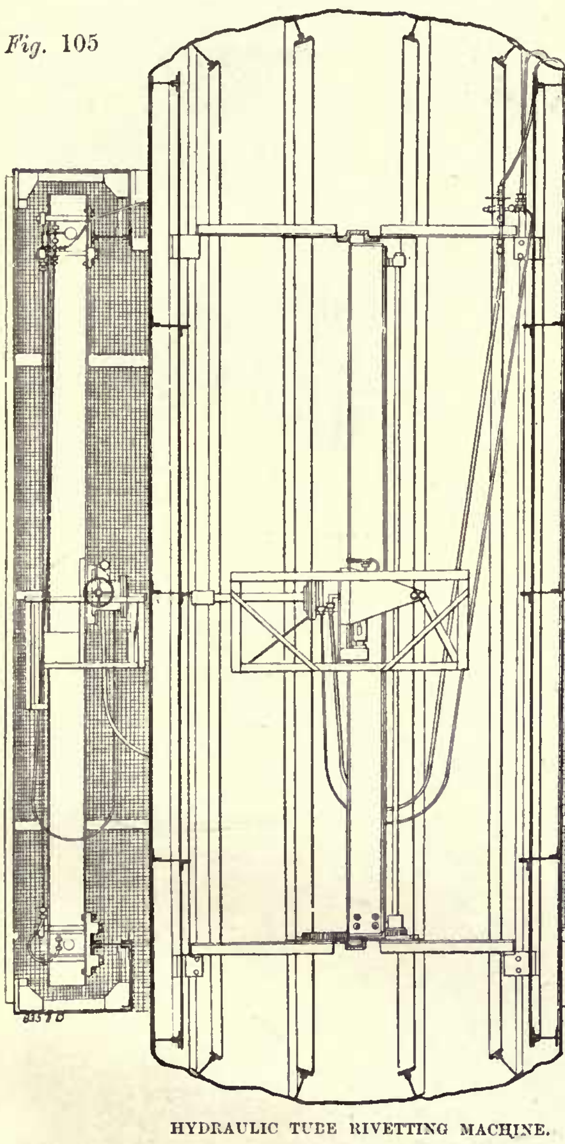
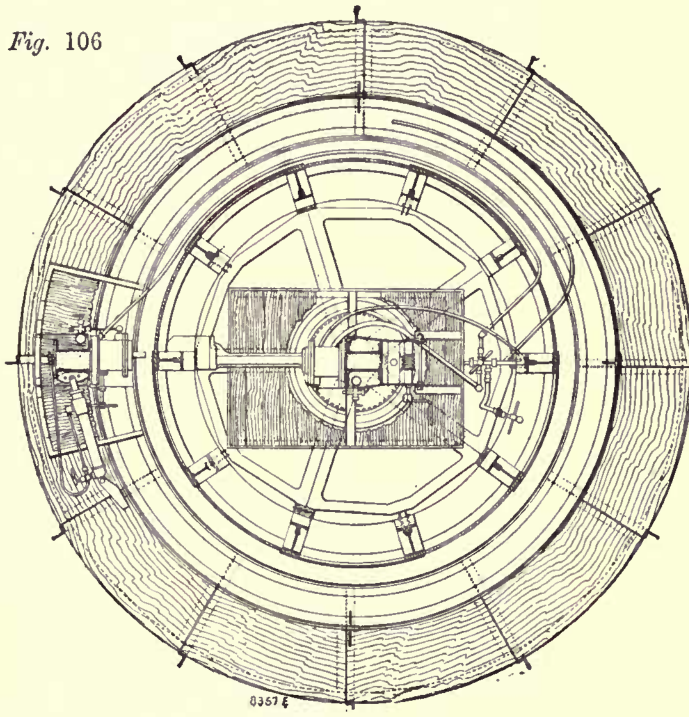


Fig. 106



HYDRAULIC TUBE RIVETTING MACHINE.

The Members forming the Cantilever.

The bottom members from their points of junction with the skewbacks are not curved but are carried in a straight line to the first bottom junctions. At the centre of these junctions the angle alters and the members continue straight to the next junction, and so on till the end of the cantilever is reached. At each change the angle becomes more obtuse, until in the middle of the sixth or last bay the members are all but level. Looked at on plan the bottom members are 120 ft. apart, centre to centre at skewbacks, and 32 ft. 2 in. at the end

THE FIFE AND QUEENSFERRY PIERS.

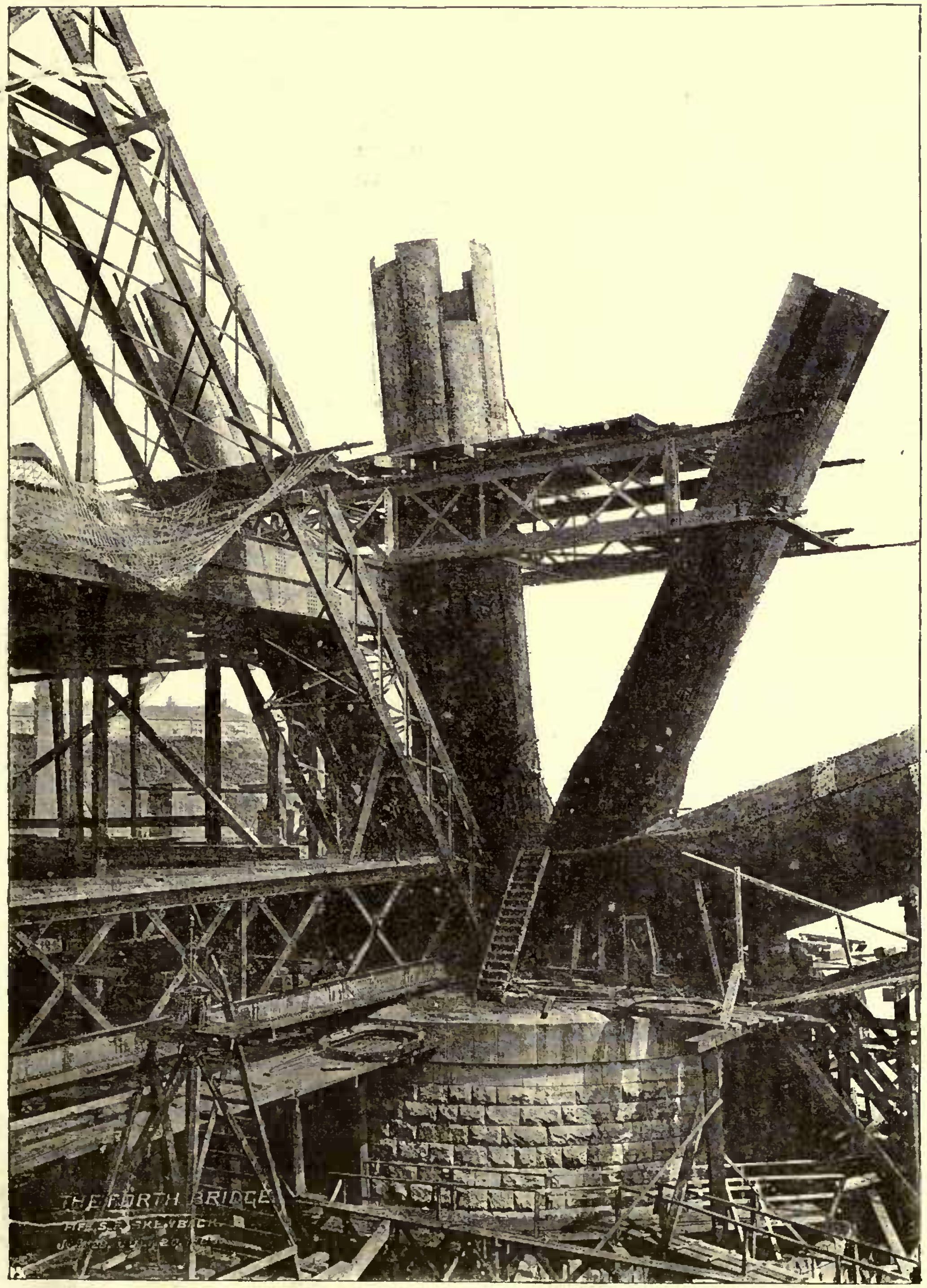


Fig. 107. Skewback on Fife pier.

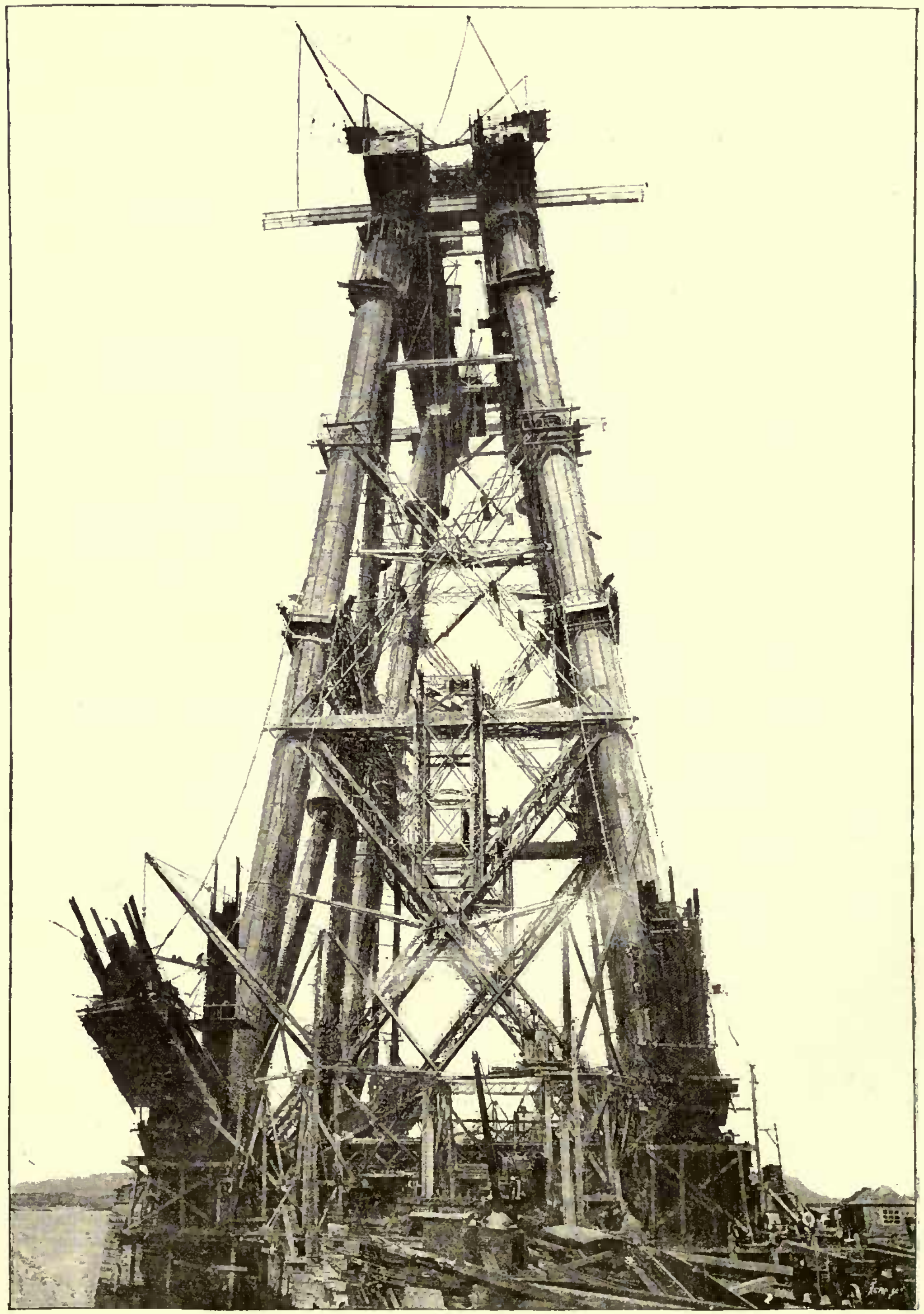
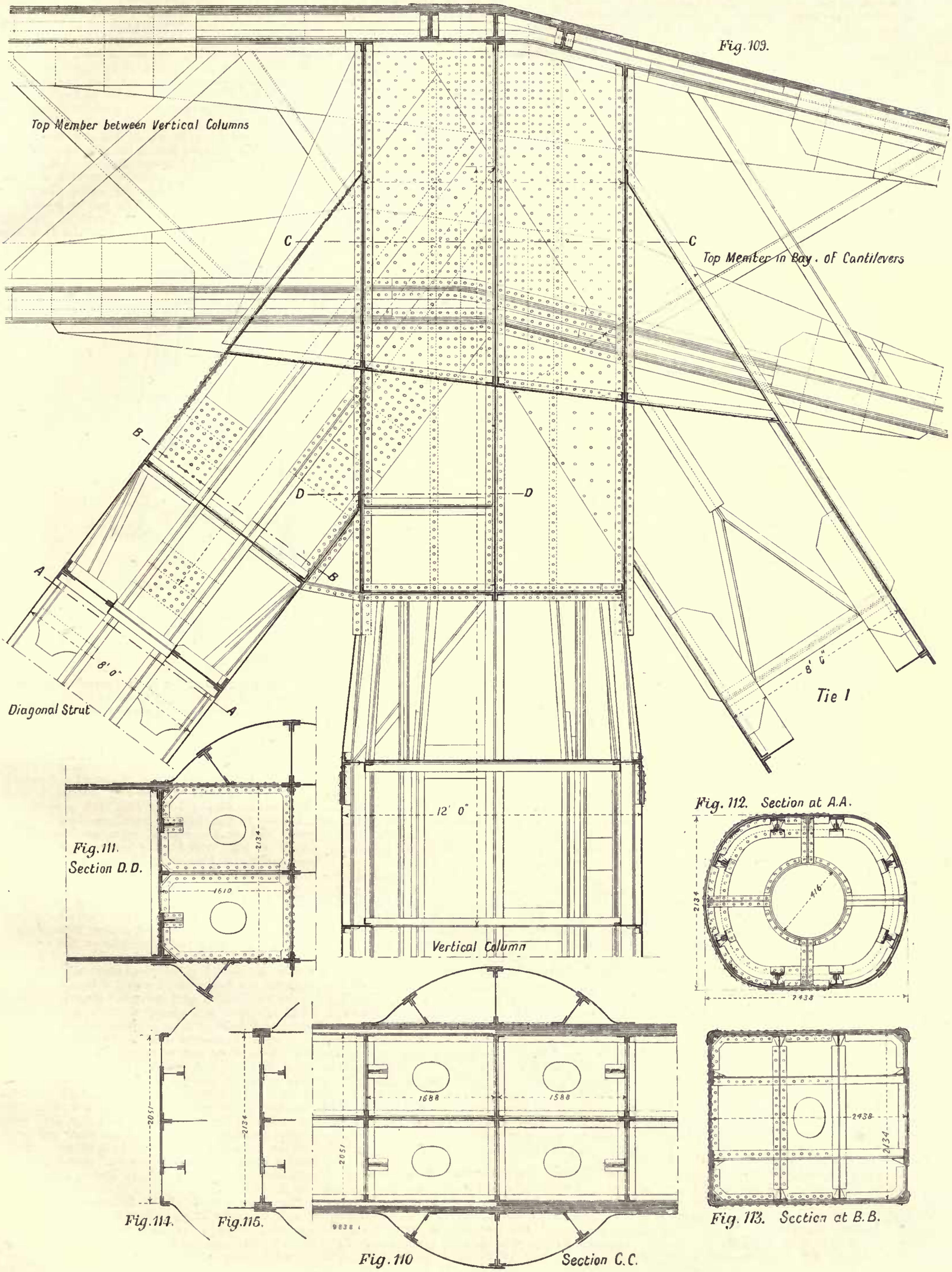


Fig. 108. Queensferry pier from the river.

DETAILS OF JUNCTIONS AT TOP OF TOWERS.



posts—the centre lines being straight between these two points (see the plan in Plate III.) The diameter of these members at the skewback is 12 ft., and the form circular, and the same form continues till the end of bay 4, where the diameter is 6 ft. 6 in.—a gradual taper being maintained throughout. Between the end of bay 4 and the centre of bay 5, the form of these members is rectangular with a curved outside, and after this a plain rectangle on all four sides of varying height and width, until at the end of the cantilever the form is a square of 3 ft. each way. The thickness of the plates in the bottom members is $1\frac{1}{4}$ in. at the skewbacks, gradually decreasing to $\frac{5}{8}$ in. at the ends. The same mode of construction with longitudinal beams and transverse diaphragms of circular or other shape is followed to the end. In all the bottom junctions the main strength is concentrated in strong webplates into which the circular tube is gradually carried over, curved plates being placed on the outside of these webs to maintain the circular appearance on the outside of the junctions. (See Fig. 126.) To the main webplates the hornplates of the ties pointing backward, and these of the struts pointing forward, are attached. Except that the winding of the outer shell is perpendicular instead of horizontal, the construction of those junctions in principle is similar to that of the top junctions at the head of the vertical columns, but turned upside down.

The changes in the form of section in the bottom members are indicated in the general elevation, plan, and side elevations of the cantilever in Plate III.

The top members (see Fig. 116) or principal tension members are lattice girders of rectangular section, consisting of four main booms, which are braced on four sides. The webplates are carried through the whole length of the girders unbroken, only changing in depth and thickness, or in the number of thicknesses. The vertical side bracings —angles alternately on one side and other side of the webs — are double-crossed throughout. The horizontal bracing is not attached to the top and bottom flanges, but to a special plate attached to the web by angles on each side, and called the horizontal web. The horizontal bracing is also of angle bars, but for the most part in single or zig-zag fashion. The top flanges run right through to end of bay 5, where they disappear, the two web angles at top and bottom supplying a sufficient amount of section. The bottom flanges run up to the top junctions only on the inside, but right through on the outside, the loss of section being made up here in other ways. Like the junctions in the bottom members, the webplates in the top junctions are stiffened or doubled, and receive the hornplates of struts and ties, with which they form a very strong framework, stiffened by bulkheads or diaphragms.

The inclined struts (see Fig. 117) are flattened on the sides to facilitate their intersection with the ties and their attachments to bottom junctions and top junctions. They are, however, changed in form altogether in their extremities—being made rectangular the same as the diagonal struts in the central towers. A number of diaphragms are placed internally where these changes occur, to keep the struts in shape. The thicknesses of plate vary between $\frac{1}{2}$ in. and $\frac{5}{8}$ in. according to position. Their construction is on the same principle as the other tubular members—lap joints on the circumference—butt joints at ends—all plates being 16 ft. long, breaking joint every 8 ft. with a diaphragm at each joint. Struts 1 and 2 are made up of eight plates; struts 3 and 4 of six plates; and strut 5 of four plates on the circumference.

As seen in Plate III. all struts in the cantilevers are braced and stiffened by diagonal wind-bracing girders of box shape, consisting of four corner angles with double or single cross-bracing on all four sides. These are attached to the struts by plate gussets and reverse angles. One girder is generally carried right through, the other is in two halves and is carried across by strong reverse angles and stiffening plates. At the heads of every pair of struts a horizontal lattice girder is placed between top junctions.

The tension members are all of the lattice girder type with four main booms of T shape braced on all four sides. The section of the main booms is made up of one or several webplates, and one or more flange plates, with angles to connect both together. At the point of crossing with the struts the inner flanges are cut away and the section thus lost is made up in some parts, by a deepening of the web and by a doubling and strengthening of outside angles on either side in the same manner as is done in the case of the flanges of the top members when passing the heads of struts and ties in the top junctions.

At the crossing of struts and ties large and strong gusset plates are rivetted, into which are attached the so-called vertical ties. This is clearly seen in Plate III. These are also rectangular lattice girders consisting of four booms, or in the lighter ones of four angles cross-braced on all four sides, and to the lower extremities of these are attached the bottom members by means of bent angles and gusset plates. These vertical ties, although not attached exactly midway between two of both members' junctions, serve to prevent undue deflection in these members, and in the first three bays of cantilevers serve to carry the weight of the internal viaduct by means of a plate girder across, stiffened by diagonal wind bracing.

to be adopted to forward the work. A cage about 19 ft. square, and consisting of a number of sections each 8 ft. in length, was placed upon the bottom member. (See Figs. 105 and 106, and Plate IX.) It was so constructed that each section could be taken away at the back and placed in front, and this operation was performed by a hydraulic crane placed on the top of the cage itself. This crane has a jib of fixed length, which it could not alter, but it could slide up and down the top of this cage by means of hydraulic rams on each side. It could also slew completely round. The forward part of the cage was used by the platers for building up the tube, the beams and plates and other parts being first brought within reach of the hydraulic crane and then swung round into place. The nearer portion of the cage contained the same rivetting machine which had already done service in finishing the

Fig. 117. Cross Section of Struts in Cantilevers.

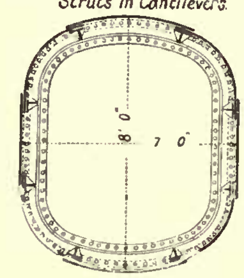


Fig. 116. Cross Section of Top Member.

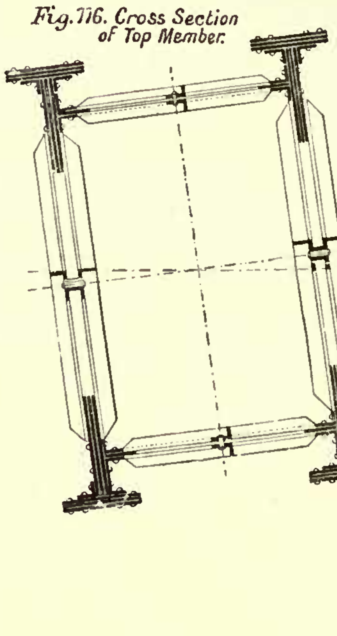
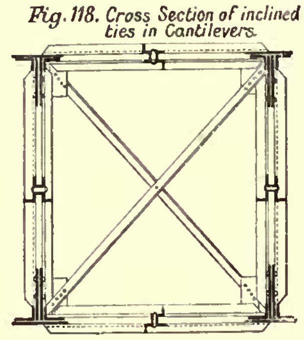


Fig. 118. Cross Section of inclined ties in Cantilevers.



DETAILS OF CANTILEVERS.

In the tension members two top and two bottom booms break joint alternately, and all webs and flanges are double covered. The top and bottom cross-bracings are rivetted to the flanges, the side bracings to the webs. Diaphragms consisting of angles on four sides and angle cross in centre are placed at suitable distances apart.

The internal viaduct in the cantilevers is the same as described for the portion in the central towers. Figs. 119 and 120 show a portion of it in elevation and cross-section at the point where the viaduct is supported in the centre of bay 1 (see Plate III.). The two figures are not drawn on the same scale, but otherwise refer to the same point.

As the spans in the cantilevers become shorter the viaduct diminishes in strength of sections, and from the centre of bay 2 to the end of bay 2 in depth also. At the end of bay 4 the girders altogether disappear, and the four troughs are strengthened and carry the permanent way, being supported both on the cross girders and on the diagonal wind bracings between the cantilevers.

All the various supports of the internal viaduct in the cantilevers are shown so clearly in Plate III that it is not necessary to enter int futher details.

The diagonal wind bracings between the bottom members are also of rectangular box construction, consisting of four main booms made up in the longer girders by webs, flanges, and angles, and in the shorter girders of simple corner angles. They are double or single-braced on all four sides, and are joined by heavy gusset plates at the points of intersection. They are joined to the bottom members by large gusset plates top and bottom, clearly shown in Plate III., plan of bottom members.

Building out of the Cantilevers.

Shortly before the lifting platform had arrived at the point of intersection of the diagonal struts or columns in the central towers, a commencement was made with the building out of the bottom members in the first bay of cantilevers. This was done as yet by steam derrick cranes, but their reach was limited, and other means had

horizontal portion of the bottom members between columns. For a length of about 64 ft. the bottom member was thus rivetted up in order to stiffen it as much as possible, and enable it to carry itself and the necessary plant at the point of it, unsupported for a time until temporary support could be found for it. (See Fig. 105.) As soon as the cage had got beyond the point of junction between the bottom member and the first vertical tie, that is, at centre of bay 1 (see Fig. 121), gussets were attached to the bottom members close to this point and to the vertical columns immediately above the horizontal bracing between the columns, and a chain of Hammersmith links were fixed up between these two points. On these links a temporary staging was suspended, by means of which a heavy plate tie—one on each side of the tube—could be inserted. For these ties also strong gussets were attached to both bottom members and vertical columns. To the gussets on the columns other gussets were attached, and to these were bolted horizontal plate ties, suspended to and immediately below the horizontal bracing girders at the intersection of the diagonal struts. A set of plate ties were also placed at the opposite cantilever, and balance thus established. These plate ties, both horizontal and inclined, were about 2 ft. 6 in. deep and of two thicknesses of $\frac{5}{8}$ in. plate, being, in fact, portions of the main webs of the top members in bay 2. Previous to the attachment of these ties to the gussets, the bottom members were lifted up to the extent of several inches by means of hydraulic rams, in order that they might be able to support their own and any further weight which might be put upon them during erection of the first bay. Most of these appliances are shown clearly in Plates, IX., XV., and XVII.

The lower portion of the first vertical tie was then built, and a lifting girder laid across from one bottom member to the other, and a platform built on each side similar to those for the erection of the central towers, only so much smaller and lighter. These platforms were lifted by hydraulic rams in

the vertical ties, and by the same agency along the vertical columns, and while lifting these in stages of about 16 ft., the two struts 1 in cantilever and the vertical ties were built up. The use of lifting-platforms was abandoned after this; all the work of erection was done far more quickly and efficiently by the cranes specially designed for this work.

Meanwhile, the top members had been completed, and a 3-ton hand-crane was set up on the top of each vertical column. (See Fig. 121.)

The viaduct girders in the central towers had also been put together by now, and a new platform was thus secured about half-way up the erection. The viaduct girders were now built out by overhanging into the cantilevers, and a length of top member as well, these two last being built by the 3-ton cranes on top, and by winch and tackle wherever such could be used. All the material for the viaduct level was hoisted to it, and for the top members, it was lifted right to the top.

The viaduct girders were strong enough to carry drilled *in situ*. This junction was then at once rivetted up, and thus a new fixed point secured from which to proceed further out. (Plate XV.)

In the mean time, the top member, or Jubilee Crane, as it was popularly called (because it was invented, or at any rate designed, about the time of the Queen's Jubilee in 1887), had been erected on the top of top member.

This crane consisted of a square frame supported on two girders reaching over all four booms of the top members from side to side. The girders were of different heights, in order to get the platform on which the crane was placed level, and the girders were placed on slides, so as readily to allow them to move down the incline of about 1 in 4 when required. The crane itself had a horizontal jib with a reach of 34 ft., and could slew round, by means of a circular rack and pinion, to about 220 deg., or three-fifths of a full circle. It was worked by a pair of reversible steam engines, and had a large barrel capable of winding put a tremendous strain upon the two top members, which were then still unsupported, and though they bore their load well it is evident that the building of this first half of bay 1, was a work of great anxiety, lest a heavy gale should cause some serious distortions.

As the top members were never intended to carry any load except their own weight, the vertical side bracings were not sufficiently strong to carry the crane without a risk of bending the bars. These bracings were consequently not only doubled by reverse bars running the full length with them, but the reverse bars were of a section double and treble that of the ordinary bracing bars. Templates for these bars were taken as soon as each section of the top member, was built up, and they remained in their places until the weight of the crane had passed beyond the next main support. Generally speaking this crane built all the members above the level of the viaduct, and of course below that level also if necessary. Its maximum lift was 3 tons, and with

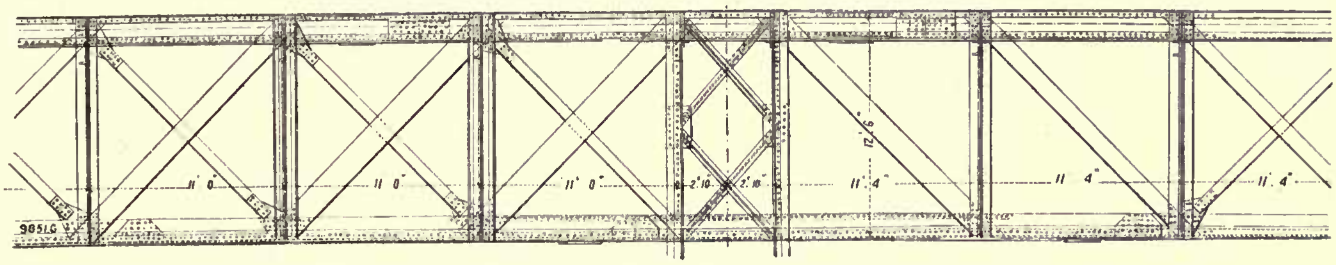


FIG. 119. ELEVATION OF INTERNAL VIADUCT.

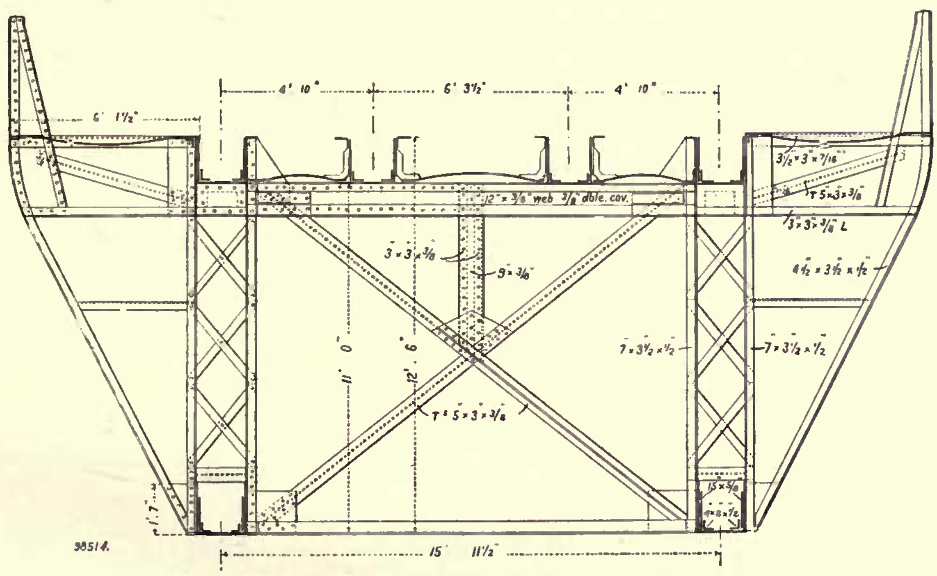


FIG. 120. SECTION OF INTERNAL VIADUCT.

themselves, overhanging for a length of 100 ft., and even then to carry at the forward end the weight of a 3-ton crane and its load, but, as a matter of safety, wire ropes were carried from the outer ends up to the top junctions on vertical columns.

The top members also had to carry their own weight unsupported for a length of nearly 100 ft.

The lifting platform in the first half of bay 1 was only carried up to about 20 ft. above the level of the viaduct, and there it remained. (See Plates XV. and XVII.)

The first inclined ties in cantilevers were now brought down from the top junctions, being held up and in position by means of timber struts between them and the vertical columns, and laterally apart by lattice girders from one to the other. (See Fig. 122.)

The first struts had also been built up to some 20 ft. above the platform, and when the ties had been brought down to the point of intersection with the struts, preparations were made to make good their junctions. Previous to this the positions of struts, ties and vertical ties, were carefully checked, both as regards their meeting in the true centre as well as being the right distance apart from the centre-line of the bridge. Large gusset-plates, joining all three members together, were then placed in position and the necessary holes up about 400 ft. of wire rope. It carried its boiler with it, and was thus quite self-contained. Suspended from the two main girders of the frame was a platform, carried some 4 ft. to 5 ft. below the bottom booms of the top member, 64 ft. long and about 36 ft. wide, mainly supported on four light lattice girders.

The planking of this platform was so arranged that it could readily be taken up in every place where required, the four lattice girders being so placed as to pass all struts and ties and vertical supports in succession, the flooring only requiring to be taken up. The sides of the platform under the top members projected to within about 6 ft. of the end of the jib. In building the top members, the booms of which were in lengths of about 24 ft., the crane could lift them from the viaduct level below and place them at once in position, the platform allowing safe ground for the men who had to guide them into place and bolt up the joints and cover-plates. The vertical bracings followed next, and then the top booms, and all other necessary work, and when both sides of the top member were built and well bolted up, the crane was pushed forward 24 ft. on to the newly built section.

The crane with platform and all necessary gear weighed about 64 tons, which, placed at a distance of about 80 ft. from the centre of the top junctions, rare exceptions no portions of the work were made heavier than about 50 cwt. at the outside.

As soon as the crossings between struts 1 and ties 1 had been made secure — a vertical support — a box lattice girder, was raised from that point square upwards in continuation of the vertical tie below, in order to give the top member the necessary support. As this support formed no part of the finished structure it was made of iron only, but of fully sufficient strength.

It required, however, both longitudinal and lateral support, and this was provided by carrying lattice girders at a point about two-thirds of the height between the crossings and the top members on each side, from the ties 1 to the vertical supports, and transversely from one support to the other. Cross ties of wire rope were also carried up between the supports. As soon as the supports had reached up to within a foot or two of the top members, a further length was built to the latter, which reached right across the supports. By this time and with so much weight on them the top members had deflected about 9 in. to 10 in., and hydraulic rams were now arranged to lift them up from the vertical supports, and give them their proper position, and place them as much higher as would allow for the probable compression in the vertical supports.

Meanwhile the lower portion of the ties 1 had been built from the point of intersection downwards, the bottom member had been brought forward, and the junction of bottom members with struts and ties at the end of the first bay, built in. But the bottom members also had deflected, owing to their own weight and to that of the rivetting machines—the cages and the bottom junctions. It was, therefore, necessary to lift the bottom members up at this point, and to do this the following plan was adopted (See Figs. 123 and 124):

Four heavy angles were attached near the ends of ties 1 so far as they had been brought down; these angles were of such length as to project some 6 ft. to 8 ft. below the under side of the bottom member; two heavy box girders were now passed under each of the bottom members, the lower one being fixed to the ends of the four angle-bars, while the upper girder was brought up to hardwood packings, which gave it a full bearing against the under side of the bottom members. Between the two girders, hydraulic rams about 10 in. in diameter were placed. The action of the hydraulic rams in being forced out was, therefore, to push the upper girders hard up to the bottom members and the lower girders downwards, thereby putting a corresponding tensile stress on the ties 1.

In the vertical ties 1, in the centre of bay 1, a joint in each of the four booms had been left open

in such manner that this tie could be shortened to a certain extent, its upper end at the crossing being now an absolute fixture. By means of an arrangement of cross-girders and hydraulic rams this joint could now be closed to any desired extent, new cover-plates being, of course, required to make good the joint.

All being thus prepared, a theodolite was placed in the centre of each bottom member, and these were lifted, both at the vertical ties and at the end of the inclined ties 1, by means of the hydraulic rams, until the members had risen to the correct angle and a trifle beyond, when hardwood packings were put between the girders, and wedges driven in, so as to secure the maintenance of their position. Thus placed, the holes in the new cover-plates making up the joints in the booms of the vertical ties were drilled at once, and the joints rivetted up.

The closing lengths of the booms of the inclined ties 1 were also measured, and templets made of them and taken to the shops. These lengths were then cut and drilled, and at once put into their places, and the whole of the ties finished up in every part and detail.

The effect of these operations then was:

1. To secure the absolute correctness of the position of the first bottom junctions as regards the height above water, and their distance from the centre line of bridge.

2. To put upon both the inclined ties 1 and the vertical ties that stress which would correspond with their share of weight of the structure put up, and to give them the elongation proportionate to that weight.

With this there were now, outside the central towers, two points established, the position of which was correct, and which were capable of sustaining the full weight which they would have ultimately to sustain in the completed structure.

The next operation was to raise the top members from the temporary vertical supports carried up from the points of crossing, and this also was done by hydraulic rams. The temporary supports raised from the points of intersection and carried to the top members were used at the centre of every bay out, becoming in each case much shorter and lighter. They had to be removed, owing to want of material for making a larger number, frequently before the top members were rivetted up sufficiently to bear their own weight and that of the staging which was attached to them, and considerable deflection in some of the longer sections was the result.

The top member crane could now slide forward another section and build, not only the next section of the top member, but also the upper halves of struts 1. These did not take long. They were built from the bottom upward, in the same way as the inclined ties were built from the top downward. For the struts light square stages fenced on four sides were used, these being 15 ft. square and open in the centre to admit the strut. The stages were accessible by means of wooden ladders laid from bottom upwards or by rope ladders hung from the top. The bars and plates were picked off the viaduct by the top member crane, swung into position, and at once bolted on, while the stage itself, when it required raising, was attached to the crane for the moment and lifted up, when it was attached again by chains or wire ropes to the strut itself.

The tie staging was hung to stout rope tackle and let down by the men working on the ties themselves.

As soon as the struts had been built up to a point close under the junctions with top members the latter had their position checked by theodolites, and, if required, they were upon these points also lifted by hydraulic pressure rams and then drifted up, and when in correct position were at once rivetted. Another fixed point was thus secured, and the first bay in cantilevers practically completed.

The plate girder, reaching transversely from one vertical tie to the other, and upon which are supported the girders of the internal viaduct, had meanwhile been put in place, as also the diagonal bracing below it. The viaduct was then advanced over it and carried forward till it reached the first trestle at end of bay 1, which reaches across the first bottom junctions and gives support to the internal viaduct at this point.

So far completed, all members were at their correct elevation so far as this could be secured, but it was possible, and happened frequently, that, owing to continued strong winds (no permanent wind-bracing was as yet fixed) from one quarter, a certain amount of displacement occurred. Thus,

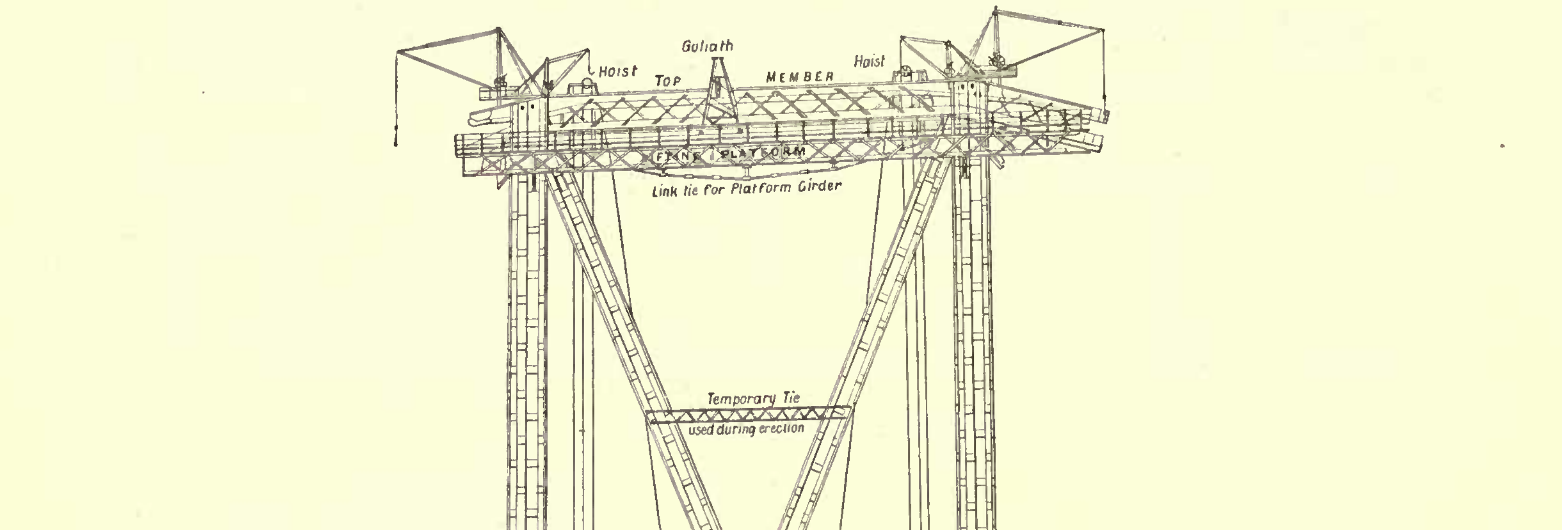


FIG. 121. ERECTION OF CANTILEVERS.

although the bottom members might at the end of the first junctions be the proper distance apart from each other, yet the centre of an imaginary line between them might not coincide with the centre line of the bridge, but fall to one side or the other. Precisely the same thing might happen in the case of the inclined struts, and the top members thus lie to one side or the other of the true centre line.

Nor was the wind the only factor that could produce such a result, for the fact whether the sun was shining on the east side or the west side of the bridge made a material difference. On the sun appearing the plates on that side of the tubular members on which its rays fell would expand, while on the other sides the plates remained as they were. This produced, therefore, a bend away from the sun, to an extent not inconsiderable, but, of course, only temporary in its action; for, with the sun turning to south and passing to west, the members not only became straightened again, but became curved in the opposite direction.

Errors in measurements and faults in construction might, of course, also produce similar and permanent results, and it was therefore necessary to take steps to fix the position so far as it could be done.

The diagonal wind-bracings between bottom members, of which the first pair starts from the skewbacks, now required to be dealt with.

As neither bottom members nor inclined struts had ever been laid together in the relative position, the wind-bracings could not be built completely, but the last or closing lengths outwards were always left to be measured and templeted *in situ*. The gussets by which they were attached to the bottom members were already fixed and rivetted to the latter, and it remained, therefore, only to erect the girders in their places and take the templets for the closing ends. While they were being erected they were hung by wire ropes to the internal viaduct. Previous to this, however, the exact position of the bottom members had to be ascertained, and, if not correct, wire rope ties attached between bottom members and girders by means of union rews or timber struts, worked with wedges or small hydraulic rams, had to be employed to draw the bottom members in or push them out, according to requirements. This done, the templets of the booms were taken and the girders completed. The same process had to be repeated at every point of attachment, that is, every half-bay out. The position of the inclined struts with regard to the centre line of the bridge was corrected in a precisely similar way, and by this means was achieved the successful building out of these arms, nearly 700 ft. in length and weighing some 5400 tons, with an error of only 2 in. For an error there is, and, curiously, it exists in nearly all the six cantilevers, and in the same direction, namely, to east. Whether this is due to the prevailing westerly winds, and the fact that the total pressure from the west upon the structure during a twelvemonth must be probably fifty times as great as the total from the east, or whether the fact that the lateral deflections due to the sun's rays are always so much greater from the west than from the east has something to do with it, the writer will not take upon himself to say, but appearances decidedly point in that direction.

With the corrections in the positions of the struts and bottom members, the first bays of the cantilevers were now completed, and, except in so far as the elasticity of the steel came into play, all the points were as fixed as if each was resting on a solid masonry pier.

The duties of the survey department in connection with the erection of the cantilevers were of the heaviest kind. The work had to be carried on in the most exposed positions and in all weathers. To Mr. W. N. Bakewell belongs the credit of a great achievement, and it is not too much to say that to his courage and decision and promptitude in fixing points, is due the saving of much time and much expenditure.

From the first bottom junctions struts 2 were started upwards, and from the first top junctions ties 2 were started downwards, in repetition of the operations already gone through in the first bay. The bottom members were built out and the internal viaduct brought forward. Upon the latter were now erected—upon a staging sliding on the rail troughs—two steam cranes with movable derricks standing side by side, each being worked by a steam winch placed some distance behind. Wire ropes were exclusively used by these cranes, which, owing to their position, were called the twins. As the Jubilee crane, resting on the top members, built all the work from near the viaduct level

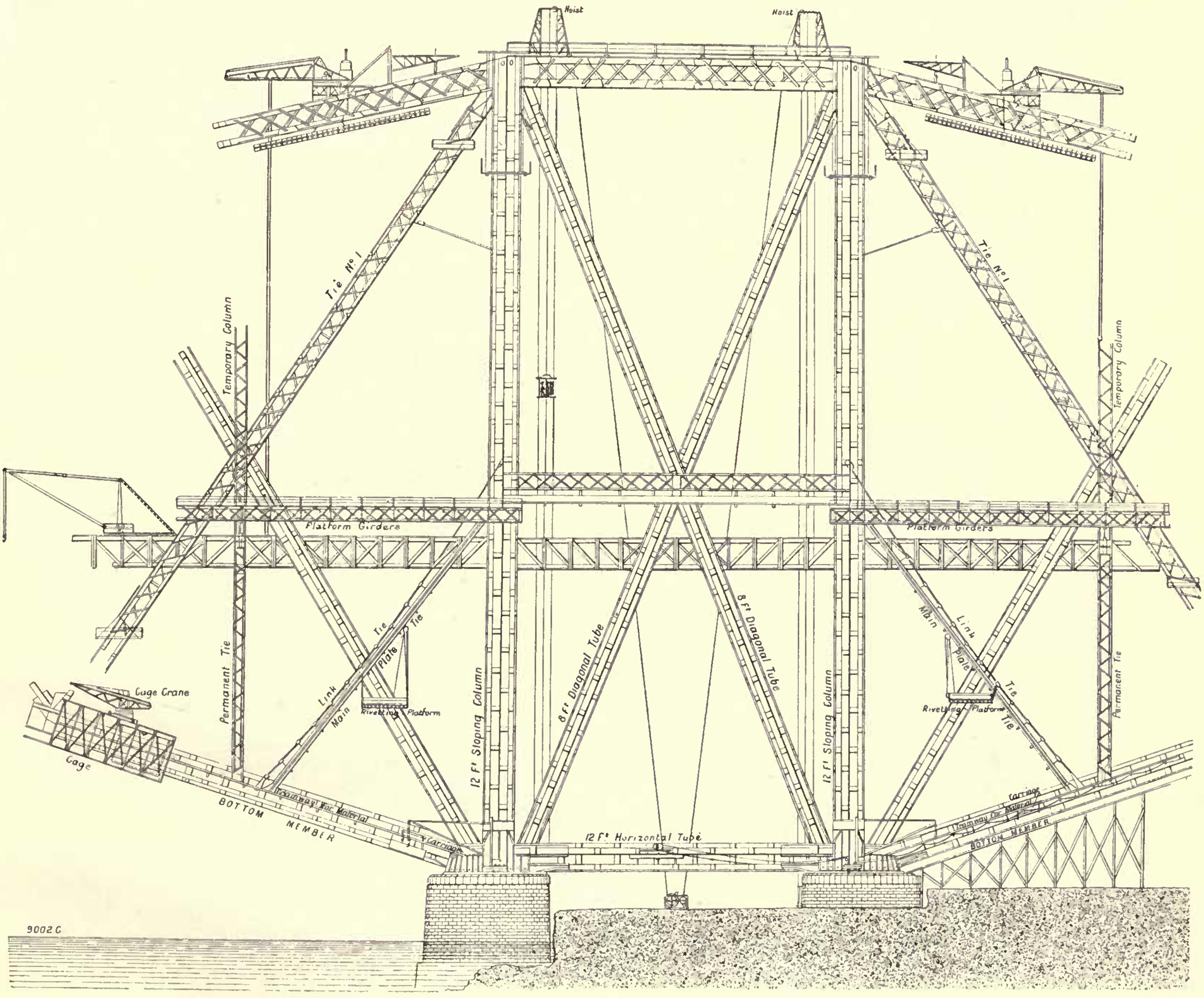


Fig. 122. Erection of cantilevers.

upwards, so the twin cranes built everything from that level downwards.

Up to this time most of the material of which the members were built was lifted by the hoists in the central towers, and brought forward on temporary lines of rails to within reach of either top member cranes or cranes on the viaduct. From this point forward only the light material, such as bars, angles, and other things, were sent up the hoists, while all the heavy booms and plates were placed on board one of the steam barges, and hoisted up by one of the twin cranes to the viaduct level, and thence were taken by the Jubilee crane to the top. Somewhat later, again, when the top union screws being used in the place of hydraulic cylinders.

The erection of bays 3, 4, 5, and 6 was simply routine work—repetitions of the work gone through —and so much more easy for the reason that not only had the distances, both vertically and horizontally, between the members become so much less great, but also because the men had become so skilful and so accustomed to their tasks, that what appeared at one time to be insurmountable difficulties and hazardous undertakings, had now become mere child's play, and was done in those exposed positions as easily as if the men were standing upon the floor of an ordinary workshop.

by hydraulic rivetters, while the struts were rivetted by hand only. The main booms of the ties were rivetted up in the yard as far as could be done by machines, and little more than the joints and bracing bars were left to do after erection. Of the internal viaduct also as much as could conveniently be got at was done by hydraulic machines, and the rest by hand.

The booms of the wind-bracings were also rivetted together in the yard by hydraulic machines, and as they decreased in weight further forward they were rivetted, at times in the full square, at others tops and bottoms, thus leaving the side bracings only to be completed.

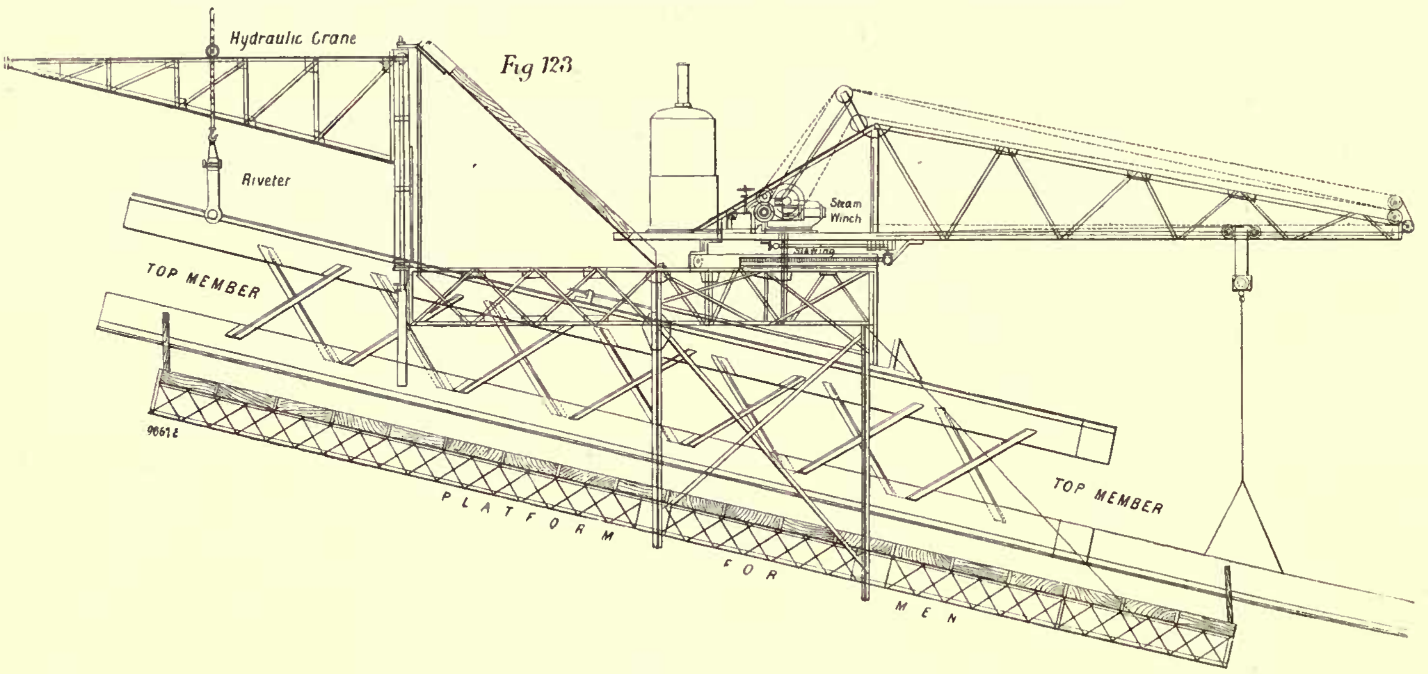
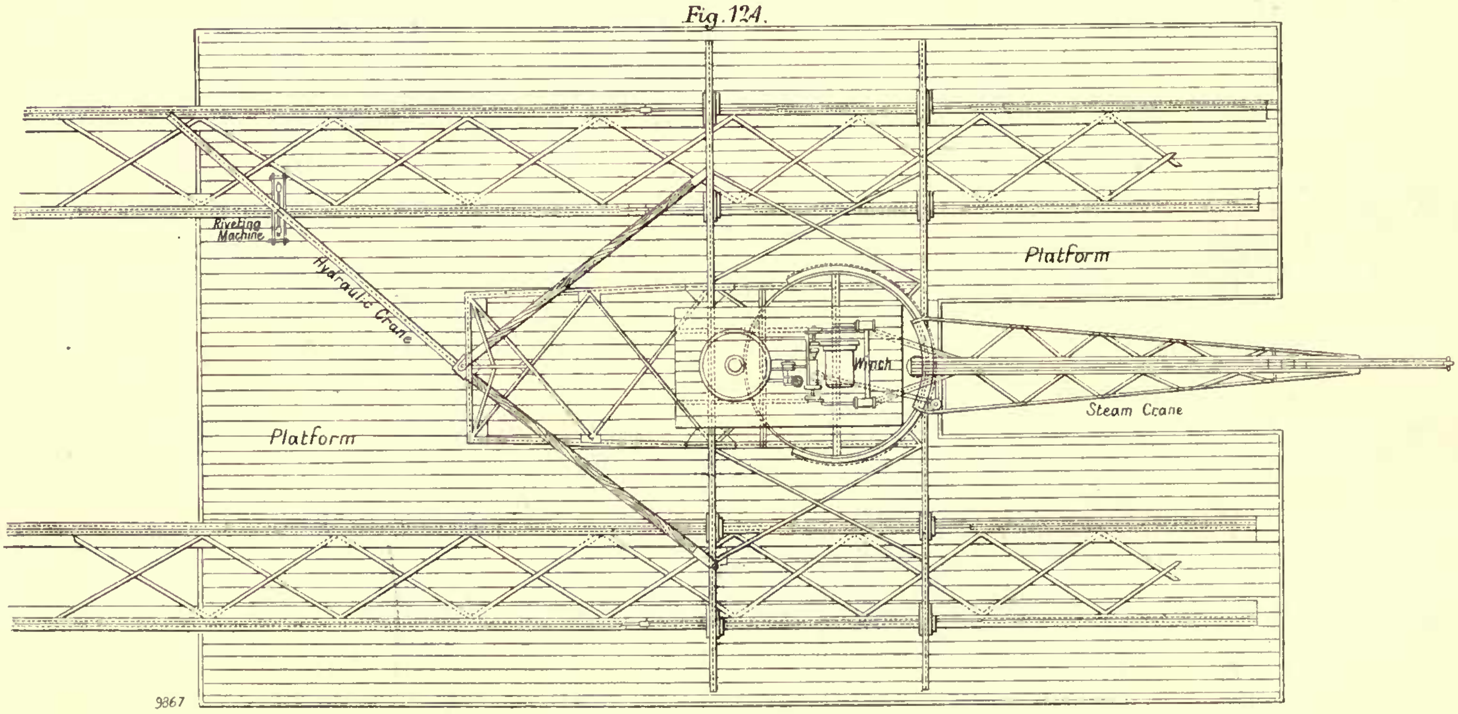


Fig. 124.



THE "JUBILEE" CRANE ON TOP MEMBERS OF CANTILEVERS.

members had still nearer approached to the water, the material for these, and for the upper portions of struts and ties, was lifted by the Jubilee crane out of the barge, and swung into place at once, thereby saving much time and labour.

In the erection of the bottom members in bay 2 the temporary attachments necessary to hold them up in position were carried partly to the point of intersection of struts 1 and ties 1, partly to the first top junction, and there attached to heads of struts 1.

Hammersmith Bridge links were used for the first and wire ropes for the second, no plate-ties being required. Later on still wire ropes were capable of dealing with most of the lifting required,

The rivetting of the work followed the erection so closely, that many squads of rivetters were working upon the extreme ends side by side with the erectors. In the case of the tension members all the main joints were rivetted as soon as possible after erection, and where such could not be done, all joints were bolted up with specially prepared turned steel bolts.

In the bottom members the hydraulic rivetting machine was carried forward to beyond the end of the third bay, after which all rivets were put in by hand, particular care being taken to have all the work thoroughly well bolted up, and to put the best and most trustworthy hands to the job. All the tension members were almost exclusively rivetted

In the same way the lattice box girders between the struts were also dealt with; they could be lifted straight into their places, the joints only and the points of intersection requiring to be rivetted.

The top member was rivetted in all parts by hydraulic machines wherever it was possible to get the machine applied. For this purpose two or three light timber stages followed at the back of the Jubilee crane, and here two or three rivet-heating furnaces were kept going to supply the various machines going below, the hot rivets being dropped down a long pipe, the end of which was stuck into a pail with ashes at the bottom. These furnaces were heated by oil and compressed air. It was thus necessary to bring along in the first instance from

the deck up to the tops of the towers, and then to each side down the cantilevers, not only the pressure pipes for the water working the hydraulic rivetters, but also for the supply of compressed air and oil to the furnaces. The oil was brought in pipes connected with a tank on the top of the central tower, and run down to the furnace tank by gravity.

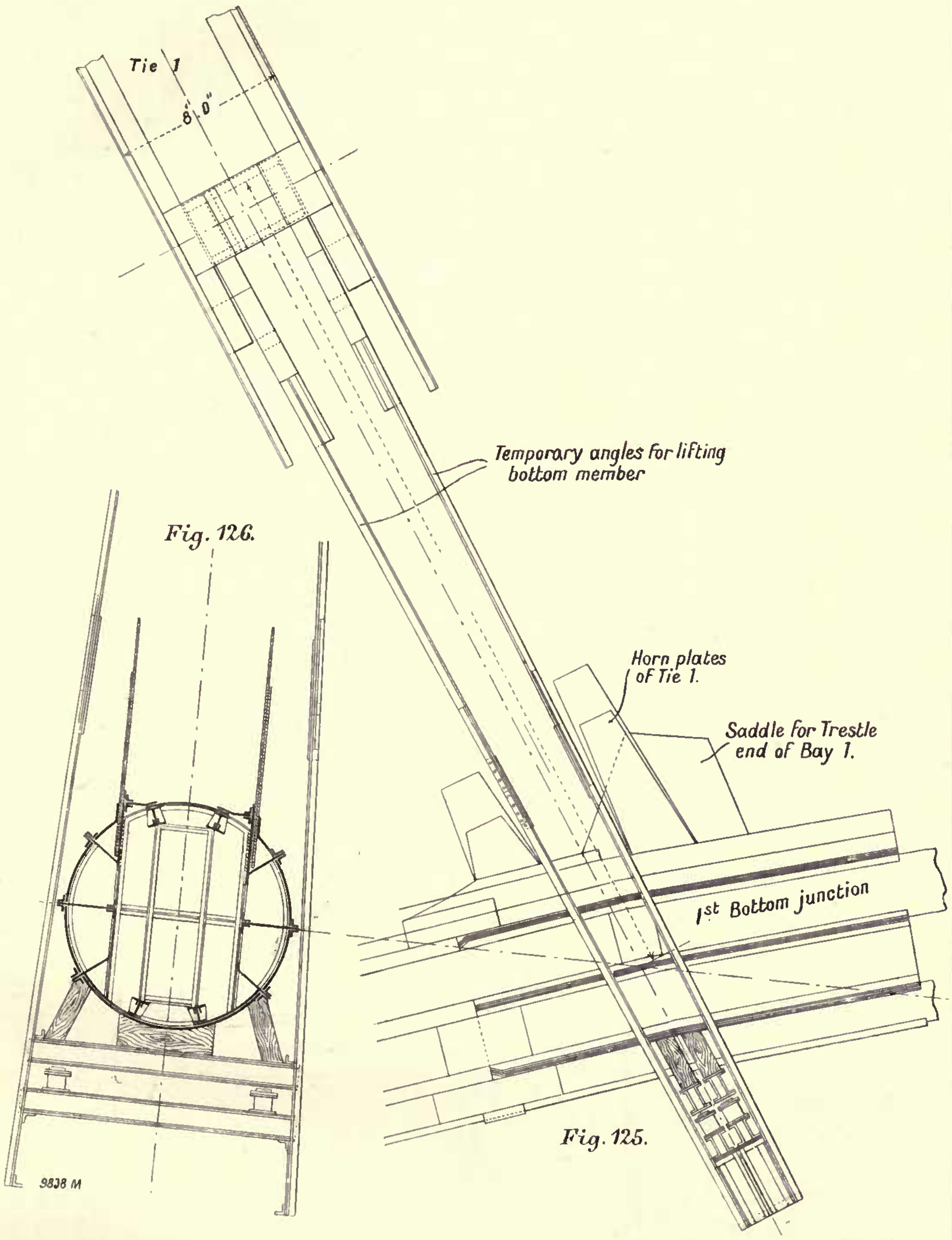


Fig. 126.

Fig. 125.

HYDRAULIC LIFTING ARRANGEMENT FOR BOTTOM MEMBERS OF CANTILEVERS.

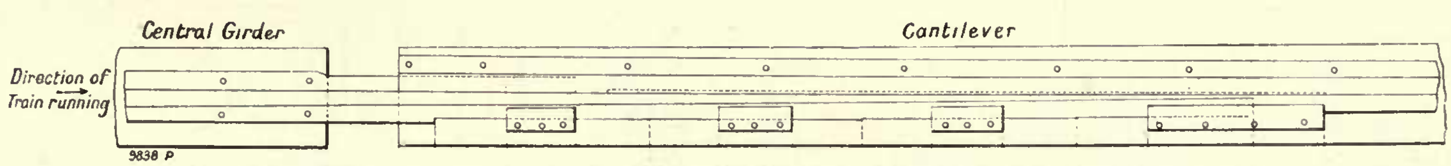


FIG. 127. EXPANSION JOINT FOR RAILS AT ENDS OF CENTRAL GIRDERS; INCHGARVIE, NORTH AND SOUTH.

With the last intersections built in bay 6, and struts and ties, top members and bottom members carried past them, it only remained to put up the end posts to complete the cantilevers.

The weight which had now been raised upon the supports may be shortly stated as follows:

Inchgarvie.

Bedplates and central tower	...	7036 tons.
Two cantilevers ...	... ...	10,750 ,,
Total	... ...	17,786 ,,

Queensferry and Fife.

Bedplates and central towers		4816 tons each
Two cantilevers	... ...	10,816 ,,
Total	... ...	15,632 ,,
or Total	... ...	31,264 tons for both

or, on the three points, a grand total of 49,050 tons, not counting the approach viaduct spans at either end.

But, apart from the permanent work, many hundred tons of weight in the shape of cranes, temporary girders, winches, steam boilers, rivet furnaces, rivetting machines, miles of steel wire ropes and of gangways, and acres of solid timber staging were suspended from these cantilevers. A heavy shower of rain would in a few minutes put an extra weight of a hundred tons, and the storm would try its worst against these immense surfaces, but with no result. Only divided by a gap of some 350 ft. it was now possible to take up a position in a gale of wind, and by fixing a point on the opposite cantilever end and another point fully half a mile further back on the shore, try to see what the lateral deflection might be. But, whatever its amount, it was too small to be noticed by the naked eye; nor could any movement be felt except a slight vibration whenever an extra heavy gust of wind would hurl itself against the solid face of steel plates.

In setting out the centre lines in the vertical sense of the bottom members while building out plate by plate, allowance had been made at every junction for the natural and unavoidable deflection in the whole cantilever as a mass. This was, of course, also done in setting out the internal viaduct.

It was intended that there should be in the free cantilevers a camber of 10 in. at the end posts when the cantilever was completed—that is, the line of rails at the end post would be 10 in. higher than in the central towers when no load was on the bridge. But to get this it was necessary to set each section higher by so much as it would deflect by the addition of the remaining sections further forward. The point aimed at was, therefore, set another 10 in. up, or 1 ft. 8 in. altogether. This was, of course, entirely a matter of calculation and of judgment, and in the end the cantilevers arrived at the position in which they were desired to be.

It remains now to tell how the central girders were erected and the final connections made.

The end posts are hollow boxes about 4½ ft. deep and 3 ft. wide, by 40 ft. in height, and are closed on three sides, the fourth side towards the central girder being open. The bottom members project right to the end of the post, while the top members stop short at the closed or inner side, except the webplates, which, in the shape of large gussets, are also carried full to the open end. So far the four free cantilevers are exactly alike, but in the further arrangements they differ considerably, as will presently be described.

The end posts of the two fixed cantilevers where they rest in the cantilever end piers are different from the above. Here the posts are replaced by a large box about 8 ft. long and extending over the whole width and height of the end of the cantilever, out of which an arched way has been cut to allow the passage of the trains. An end elevation of this box is shown in Fig. 23 on a preceding page. The object of these boxes has been already explained, and will be again referred to in connection with the expansion movements provided for at this point. They are filled with cast-iron bricks and punchings and other scrap all laid in asphalt poured in hot and firmly set, thus preventing shifting and at the same time making the box water-tight. About 1000 tons of dead weight is placed at these points over and above the weight of the steelwork.

The central girders have already been described as having a slightly raised or curved top member of polygonal form; that is to say, it is straight from one support to another, a kink taking place at the point of support, in the same manner as the bottom member in the cantilevers. The bottom member is straight. The two are connected by eight pairs of cross-bracings on each side, intersecting each other at the centre and consisting of struts and ties. The girder is 350 ft. in length, 40 ft. high at the ends, and 50 ft. high in the centre. It is divided into eight bays of slightly unequal length. The top members are braced together by 16 sets of diagonal lattice bracings, while the bottom members are connected by solid plate girders acting as cross-bearers, one at the centre and one at the end of every bay, in addition to those forming the ends of the girders. Vertical ties are attached to each intersection of struts and ties and carry the bottom members between the bottom junctions. The bottom members are trough-shaped and about 3 ft. high by 2 ft. 6 in. wide;

DETAILS OF CONNECTIONS OF CENTRAL GIRDERS AND INTERNAL VIADUCT.

Fig. 128.

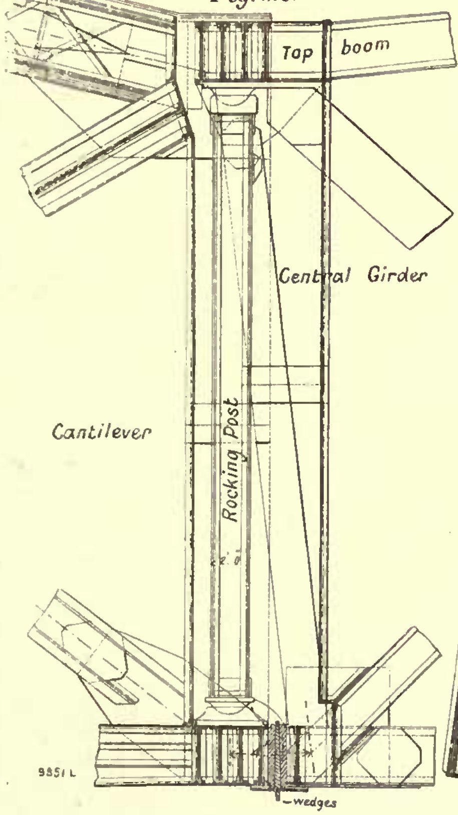
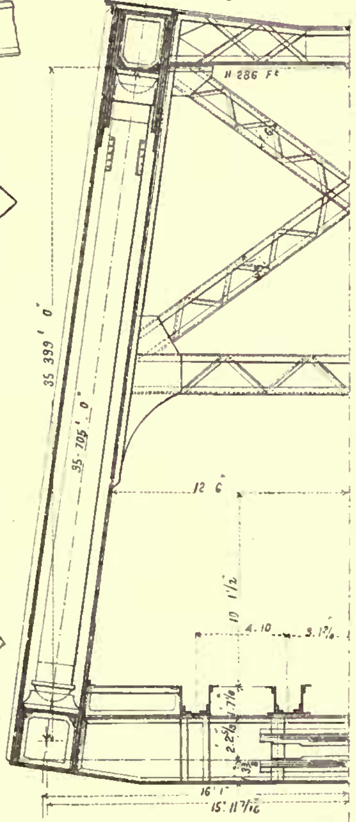


Fig. 129.



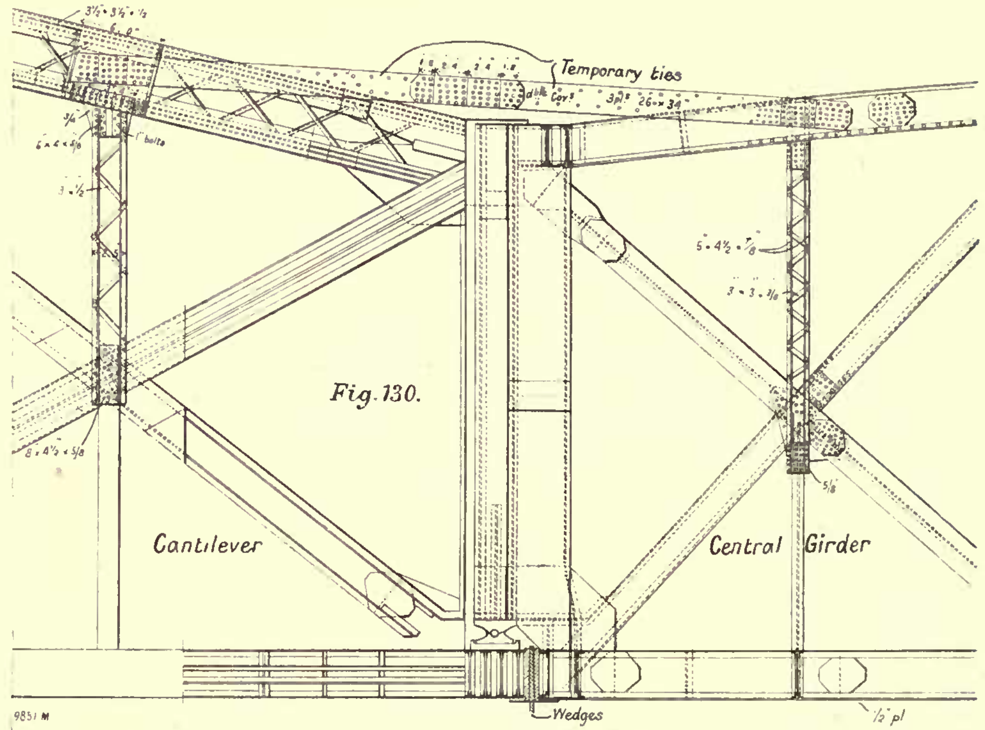


Fig. 130.

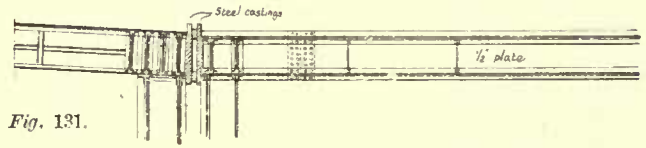
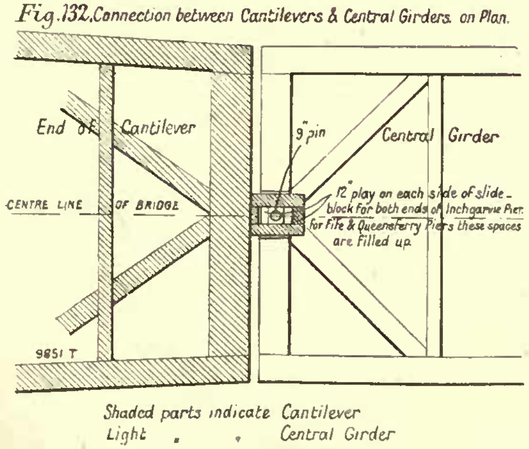


Fig. 131.

Fig. 132. Connection between Cantilevers & Central Girders on Plan.



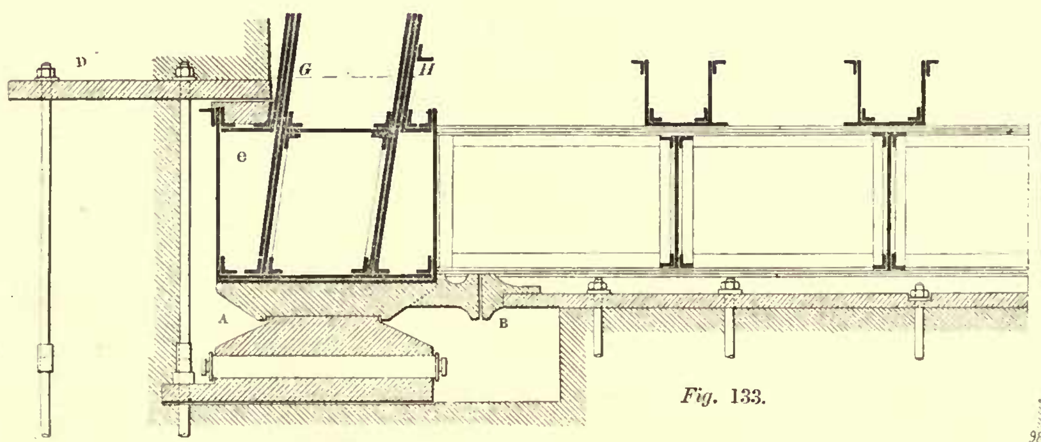


Fig. 133.

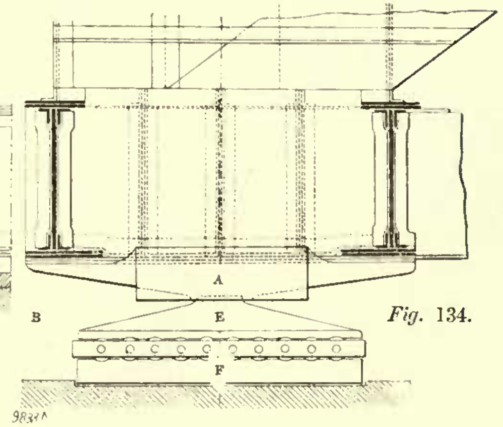


Fig. 134.

the top members are inverted troughs of the same dimensions. Each pair of opposite struts is connected by two pairs of diagonal wind bracings carried down as low as the passage of trains will admit. All struts and ties are of box shape of varying strength and section. The joints in top booms and bottom booms were so arranged that each half-bay could be built out in succession, the length of boom just reaching beyond the junctions or beyond the vertical ties. The permanent way and the flooring in the central girders are made up much about the same as in the cantilevers, with four rail troughs and two footpaths, and a wind fence on each side. The 6-ft. way—the space between the two troughs of each line of rails and the footpaths—were made up of buckle plates supported on T bars from trough to trough.

Previous to the exact lengths of the central girders being fixed the distance between the cantilevers had been measured carefully and frequently

CONNECTIONS OF CENTRAL GIRDERS AND CANTILEVERS.

Fig. 136.

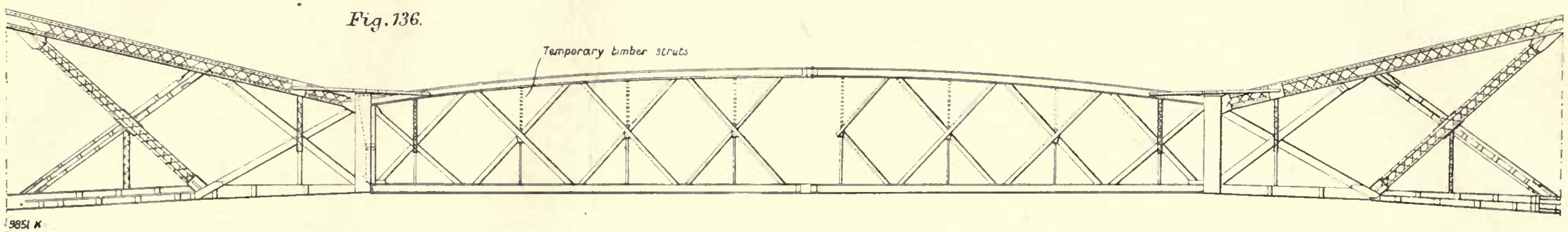


Fig. 135.

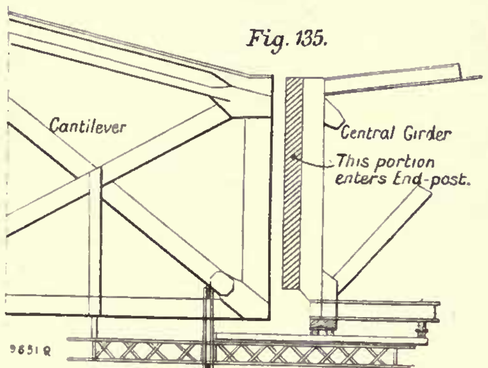


Diagram showing Erection

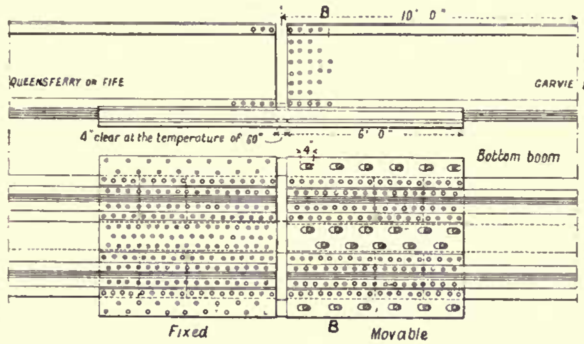


Fig 137 Elevation

Fig 138 Plan

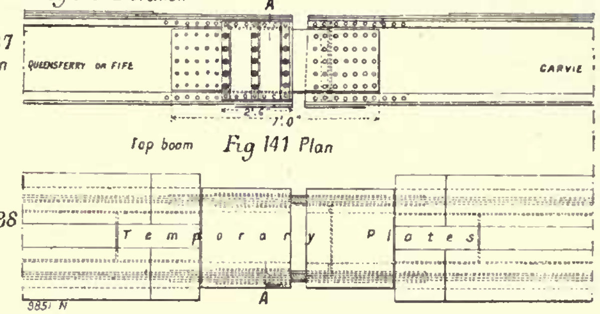


Fig 140 Elevation

Fig 141 Plan

Fig 139 Bottom boom

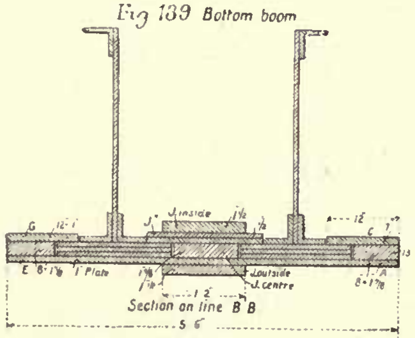
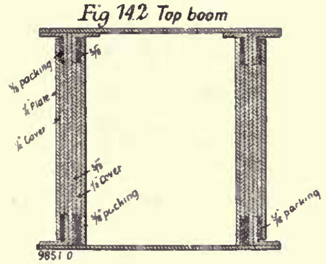
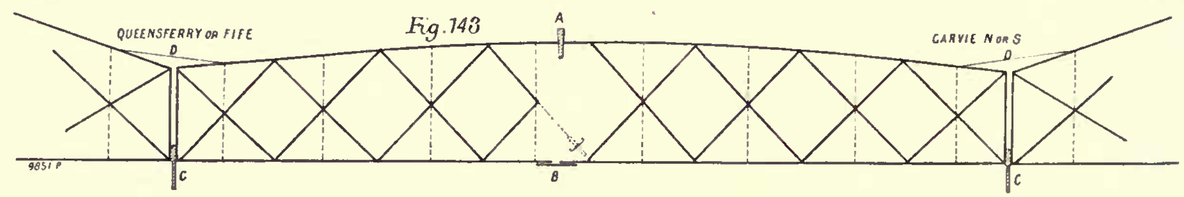


Fig 142 Top boom



Section on line A A

Fig. 143



by wire or steel tape measurements. These measurements were taken at various times, under different conditions of temperature, and were carefully checked.

The lengths of the girders were then decided upon with a view of leaving sufficient play between them and the cantilevers, under the fullest extension by summer heat and sun heat.

At the mean temperature the end faces of the bottom booms are about 1 ft. apart from the ends of the cantilevers, and no weight-carrying connections exist between these two, all the weight of the central girders being carried by the top booms and bracings. The top booms project into the end posts of the cantilever and are there supported in a manner presently described.

The central girders—so far as longitudinal expansion is concerned—are fixed at the Queensferry and Fife ends, and to all practical purposes form parts of these two cantilevers. On the other hand, both at the Inchgarvie north and the Inchgarvie south ends, longitudinal movement is provided to the extent of 2 ft. at each end by means of an arrangement of rocking posts, slide-blocks, and expansion joints in rails.

Upon the ends of the cantilevers within the hollow end posts are placed steel castings in the shape of large cups or sockets. (See Figs. 128 and 129.) Into these are fitted knuckles or half-balls, fixed to the bottom of square posts or columns built of stout steel plates in box form. Upon the upper extremities of the posts are fixed steel castings of cup shape, the same size as those below, and into these are fitted half-balls which are fixed to the under side of the top booms of the central girders projecting into the end posts. Thus the weight of the central girders at these ends is transmitted from the top members of the central girders through these rocking posts to the bottom members of the cantilevers, and full freedom is given to the longitudinal movements.

At the Fife and Queensferry ends of the central girders there are steel castings also placed on the ends of the bottom members within end posts, but here the castings are in shape of half-bearings, to receive cylindrical pins 9 in. in diameter, and about 3 ft. long, set horizontally but at right angles to the centre line of the bridge. (See Figs. 130 and 131.) Here the girder ends are brought square down from the ends of the top members of the central girders, and are cut out to receive a casting which is placed on the top of the pin and is the exact counterpart of the one under the pin.

Longitudinal movement is therefore impossible here, but the attachments at both ends admit of a small amount of lateral deflection, which may be caused by wind pressure and by the heat of the sun's rays on either side. These are provided for in the following manner:

From the cross-girder which connects the ends of the cantilevers, both between top members and bottom members, strong plate brackets project and pass right through openings arranged in the corresponding end girders of the central girders. (See Fig. 132.) These brackets are somewhat stronger in the lower than in the upper girders. Between the two projecting brackets passes a vertical slide-block about 17 in. square, which fits exactly, and the slide-block is held in position by a vertical pin, 9 in. in diameter, the ends of which are fixed in the cross-girder of the central girder. In the top girders the slide-block is 19 in. square and the pin 6 in. in diameter.

At the Garvie ends these slide-blocks are in mean position at mean temperature, and have play at each end to the amount of 12 in. for longitudinal movement, while the vertical pins top and

bottom, allow a horizontal movement of the whole girder round the centre of the pins, while yet allowing no lateral movement of any kind except that which may be due to the mere hair's-breadth of play in the slide-block.

At the Queensferry and Fife ends, however, these blocks are absolute fixtures, steel packings having been placed into the two 12-in. spaces which are left open on the Inchgarvie ends; and while yet the same circular horizontal movement round the centre of the pins is possible, both longitudinal and lateral movements are prevented. Should it therefore happen that one cantilever has to sustain the impact of a heavy gust of wind while the other is not so affected, the deflection thereby produced can take with it one end of the central girder and leave the other in its original position without putting any side stress upon the girder itself.

It should be mentioned that the lower bearings at Queensferry and Fife in which the pins rest, are not bolted down to the cantilever ends, but have play sufficient to allow horizontal circular movement round the centre of the pins in the interlocking arrangement above described.

All expansion joints in the main structure have now been considered, with the exception of that in the cantilever end piers. At this point expansion and contraction to the amount already stated can take place longitudinally, but in no other direction. This is the only occasion where rollers are used for bearings, and the arrangement of these is clearly shown in Figs. 133 and 134. The lateral or vertical movements arising here are prevented by the following means:

The steel casting A is a fixture to the under side of the extreme end of the cantilever, here in form of a box. This casting forms the head of the roller bearing, but also bears a side flange, which is set hard against a heavy cast-steel plate B, which is bolted down hard to the masonry, and carries a side flange similar to that of A. As the same thing is arranged on the opposite side, it is clear that lateral movement can only take place to the amount of play between A and B, which is practically *nil*.

Again, on the top of the bottom end girder of the cantilever, outside the loaded box, a piece of steel C is laid, which touches, or nearly touches, another cast-steel plate D, let into the masonry of the pier, and bolted to it by holding-down bolts. Independent therefore of the counterpoise placed at this end, which prevents the cantilever lifting under any conditions of train load or fixed load, there is provision made to prevent its rising should an unusually heavy gust of storm-wind strike the end of the free cantilever, and thereby try to lift up this. This it cannot do, but the stress causes an upward deflection in the fixed cantilevers within the limits of the elasticity of the metal. Neither of these two arrangements interferes with the longitudinal expansion or contraction, which are facilitated by the arrangement of rollers between the castings E and F. All movements have now been considered in detail, and since they are of such vital importance, it will not be superfluous to recapitulate them here once more *in toto*.

1. Expansion and contraction produced by changes in temperature provided for by the sliding bedplates, by the rocking posts at one end of each central girder, and by roller bearings in the two cantilever end piers.

2. Lateral deflections, whether due to wind pressure, or to the influence of the sun's rays, provided for

(*a*) By the play left in the bedplates of the fixed cantilevers.

(*b*) By the arrangement in the keyplates between lower and upper bedplates, which permit a slightly circular movement on the centre of each column, producing torsion in the same.

(*c*) By the central vertical pins in the interlocking arrangement between ends of cantilevers and ends of central girders.

All vertical deflections are taken up and resisted by the elasticity of the metal in the structure.

As soon as the end posts of the cantilevers had been built, the necessary preparations were made to start with the erection of the central girders. The principle upon which this work was to proceed was the same as in the cantilevers, by overhanging, but in the absence of a fixed joint between the two, other arrangements had to be made. Both ends of the central girders required to be temporarily attached to the cantilevers until they were brought together in the centre of the span, and could there be joined up. The ends could then be released.

In the first instance, heavy temporary platform girders had to be attached to the under side of the bottom members in cantilevers projecting over towards the central girders, some 25 ft. (See Fig. 135.) Upon these were laid cross-timbers, and a strong platform was formed upon which the first half-bay of the central girder was erected. This had to be done, however, outside, and about 6 ft. away from the end posts, because all rivets inside the end posts, and through those portions of the central girder which would have to be drawn within the end posts, required rivetting up. All these holes were countersunk, and the rivets made flush. The cups which had to receive the rocking posts were meanwhile placed in position, and carefully set and levelled, and next the rocking posts, weighing nearly nine tons each, were hoisted up by special tackle and shipped into their places, and lowered into the cups or sockets. Into the tops of the rocking posts were now placed the half-balls or knuckles with flat tops, upon which the under side of the top members of the central girders would come to rest. Thus far the Inchgarvie ends. The Queensferry and Fife ends were similarly dealt with, except that no rocking posts, but only the horizontal pins, had to be placed. The shipping in and fixing of slide-blocks and vertical pins had also to be done at the same time. As soon as the half-bays of the girder on each side were built, the whole portion, weighing about 42 tons, was shifted back into its place inside the end post, and connected up and also drawn tight by a number of chains and wire ropes passed round. Heavy temporary ties were now attached at the centre of bay 6 in the top members of the cantilevers at one end, and at the centre of bay 1 in the top members of the central girders. (See Fig. 130.) These ties consisted of three layers of plate, each $\frac{3}{4}$ in. in thickness, by 26 in. in depth. There was one such treble plate-tie to each side of a top member, or four altogether. The ends were fixed to large gusset-plates and rivetted up, but the middle joint was bolted up by special turned steel bolts, 1 in. in diameter. There were about seventy-four bolts to each joint.

To the ends of the bottom members, both in cantilevers and central girders, thick cast-steel plates were fitted, leaving a wedge-shaped space between them, the wide end downwards, and this space was carefully templated, and steel wedges, about 9 in. wide, two to each side, were fitted in and set up hard. (See Figs. 128, 130, and 131.) Everything was now ready for continuing the building out of the girders, and half-bay by half-bay was speedily added, some delay being caused on account of all the joints in top and bottom booms having to be rivetted before much weight was added forward.

The top member cranes, which had by degrees made their way downhill, doing all the work since the fifth bay had been completed, as the cantilevers had by then narrowed so much that there was no room to bring the twin cranes any further, were now relieved of their heavy platforms underneath the top member, and of other temporary appliances they carried. Thus made lighter, they were moved on the temporary plate-ties, and thence on the top booms of the central girders, where they now began to climb up the curved booms towards the centre of the span. (See Plate XIX.) These cranes now built the whole of the work, lifting all the material out of the barges in mid-channel, except the heavy floor girders, which weighed nearly four tons each, and were hoisted by special tackle with wire ropes and steam winches set up near the ends of the cantilevers.

It was not long before the Jubilee cranes, which had originally started from the tops of the Inchgarvie tower, and had proceeded, the one towards the south and the other towards the north, met face to face, the two others, which had come down from the tops of the Queensferry and Fife towers respectively, and with the putting in of the last lengths of booms, their functions practically came to an end. (See Plate IV.)

Much, however, remained yet to be done, for the connections had to be made, and the making of these depended largely upon the weather, or at any rate upon the temperature. As it was not convenient to arrange the joints exactly in the centre of the girder, where they would have coincided with the junctions of the last pair of struts and ties, the joint was laid in each instance some 6 ft. nearer towards Fife and Queensferry. The four bays of the Inchgarvie halves were, therefore, completed, and half a tie and half a strut belonging to each of the other two halves were left incomplete. (See Fig. 136.)

In setting out from the ends of the cantilevers the wedges had been set in such manner as to give the bottom booms an inclination upwards, which, if no deflection had occurred, would have given the girder a camber of 12 in. The deflection, however, arising from the increasing weight overhanging, reduced this to exactly the camber prescribed—namely $3\frac{1}{2}$ in.

The lengths of the bottom booms of the girder were fixed so as to leave at the temperature of 60 deg. still a gap of 4 in. clear between the ends. This was necessary, on account of the possibility of the temperature rising considerably above 60 deg., which in the middle of September, when the south central girder had been expected to be connected, was quite possible. For the north central girder, which was to have been connected a month later, the same gap was left for a temperature of 50 deg. only.

In the top booms a somewhat larger space was left, tapering in shape from about 10 in. at top down to 6 in. at bottom of the webplates; for here wedges had to be inserted.

As it happened, however, delays occurred, and the south girder was not connected till October, and the north girder in November.

The connection of these central girders was an operation of a most interesting character; for here a greater use was made of natural forces than in any other portion of this bridge.

As it was essential to have the temporary plate ties, which still held up the weight of the two halves of the central girders, fully under control, a small brick furnace, heated by oil and compressed air, in the same manner as the rivet-heating furnaces, was built round each of the four plate ties at each end, just above the end posts, and everything made ready for instant lighting of the same. Arrangements were also made to draw together by hydraulic pressure the two bottom booms at the gaps in the joints in centre of girders, in order to be able to give every chance to the work being done expeditiously.

The temporary connections between the booms, which, however, allowed full play to expansion and contraction, were as follows: (See Figs. 137, 138 and 139.)

To the bottom flanges of the bottom booms, large and thick plates had been bolted on each side of the gap, extending over the whole width of the bottom flanges, and projecting to some 7 in. on each side of them, and upon these plates other plates, which reached across the gap. They were fixed on the Queensferry and Fife sides, but could move in and out at the Inchgarvie ends. For the temporary connection there large slot-holes were provided, into which bolts $1\frac{7}{8}$ in. in diameter were fitted, but were not put in until the time of making good the connection, the slot-holes being 4 in. long, while the holes in the plates, which were parts of the booms were simply round, of $1\frac{7}{8}$ in. diameter. Once these bolts were driven in, the gap between the booms could not be increased, but in case of increase of temperature the slots would allow the gap to decrease and prevent buckling in the booms. The arrangement is clearly shown in the illustration.

The temperature had been watched for several days, and the changes in the length of the boom ends noted, and after everything was ready for making the connection, the temperature yet failed for several days to rise to within 6 deg. to 8 deg. of the 60 deg. required, and the large bolt-holes were barely half open. The application of hydraulic pressure only gave about $\frac{3}{8}$ in., equal to 3 deg. of temperature, and there was nothing for it but to wait patiently. At last, on the afternoon of October 10, with the sun shining brightly from the south-west, the temperature being 55 deg. generally, the west boom came together near enough to give a full bolt-hole; but the east boom wanted a quarter of an inch, in spite of all the pull that could be got out of the hydraulic rams; so a quantity of waste soaked in naphtha was put into the bottom booms for about 60 ft. to either side of the gap and set on fire, and in a few moments the boom had expanded to the full amount required. All the bolts, twenty-three in number, were at once put into the holes and screwed down hand-tight. The web-covers across the gap to each side of the booms, and the corner angles, were put on, and one side, which had been kept blind, was drilled through at once, and the covers bolted up.

This joint having been made at the time of the highest temperature of the day, when the cantilevers and girders were of the greatest length owing to expansion, it follows that as soon as temperature decreased, the cantilevers and girders would shorten, and the only gap left in the bottom booms, namely at the Inchgarvie end, where the wedges were placed, would open. Had the change between the maximum temperature of day and the minimum temperature of night been considerable the wedges would thereby have been released, and, if free, would have dropped out. Precautions had, however, been taken, and had the wedges been ever so slack they could not have moved from their places. In addition to this, hydraulic cylinders had been attached to the ends of the wedges, by means of which they could when necessary be drawn out from between the plates. The change was, however, only about 3 deg., and with the tremendous compression on these wedges could make but little difference.

In this condition the girder was left overnight, but carefully watched, and all changes of temperature and of movement in the upper booms ascertained and noted down.

At 6 A.M. on October 11 a start was made with the drawing of the wedges first at the Queensferry end, and then at the Inchgarvie end of the girder, and they were drawn down with little effort. (See Fig. 143 at C C.) At the same time the wedges or key-plates which closed the top booms were placed in position and driven down hard into their places at A A. The top boom connections were somewhat different in their nature, the stresses, after connection had been made, being exactly the opposite of those in the bottom booms, namely, compressive instead of tensile.

It will be remembered that the weights of the two halves of the central girders were held up by the four plate ties connecting them with the cantilevers at D D, Fig. 143. The expansions in the cantilevers, after the bottom booms were connected, would have the effect of drawing up the centre portion of these booms in the same way, as if, instead of a central girder, there had been a simple rope attached to these ties. On both cantilevers contracting or shrinking, the rope would have been tightened and lost some of its downward deflection or sag at B. This was precisely what occurred to the bottom booms of the girder, for the top booms were still gaping and could not prevent the further opening of the gap. A temporary sliding connection was, however, arranged in the top booms in such manner that nothing could prevent their moving nearer together or further apart with the changes in temperature. (See Figs. 140, 141, and 142.) The gaps left between the webs of the booms, which were here thickened to 2 in., were, as before stated, from about 10 in. at top down to 6 in. at bottom of the web. (See Fig. 143.) The gaps at A had been templated and the key or wedge-plates made to these templates. It will now be understood that, in order that the bottom booms of the girder should retain their camber or upward deflection, it was essential that these wedge-shaped spaces should be closed at the lowest possible temperature, for, when once in their places, the top boom was closed like an arch in which the keystone had been placed.

Fortunately the setting up and holding up of the girder halves during construction had given the bottom boom as much camber as was required, and it needed no assistance from the drawing of the ties, otherwise some days of delay might have occurred, for the temperature kept high and the contraction in the cantilevers was not sufficient to draw the ties much.

The key-plates were then driven down hard and the heavy web-covers on each side were at once drilled through and bolted up. At the same time T bars of heavy section were placed at the top and bottom to form a temporary connection of the flange plates. Timber struts from side to side to keep the booms apart, and wire rope ties to hold them together, were also put on.

The remaining halves of struts 4 and ties 4 of the Queensferry half of the central girder were also templated now to the required size, and put in place as soon as possible.

The gaps in the top booms having now at the lowest temperature been filled by the key-plates, the effect of a rise in temperature and consequent expansion of the cantilevers would be to buckle the temporary plate-ties between central girder and cantilevers at D D, Fig. 143. As soon as this movement was felt, the bolts at the central joints of these ties (see Fig. 130, at M) were gradually withdrawn and the ties altogether detached. At the same time the furnaces were set going, and the plate-ties made so hot that, whether a rise or fall in temperature should take place, these ties could no longer restrain any movement, but would yield to either influence. With the removal of these ties the central girder entered upon its full function as a connecting link between the two cantilevers, and the south span was thereby successfully completed. A careful levelling on October 12 showed a camber of 3⅞ in. in the girder, and no deviation laterally from a straight line drawn between the centre of the ends of the two cantilevers.

The north central girder had in the mean time been built out in a precisely similar manner, and by October 15 it was sufficiently advanced to allow a gangway 65 ft. long to be laid across. This enabled the directors of the company to walk across the bridge from end to end—the chairman of the company being actually the first person to cross the north span.

By October 28 the last booms were put in, and by November 6 everything was ready to connect this girder also. The temperature on that day did not rise, however, sufficiently high to make the joint, but in the night a sudden rise took place, and by 7.30 in the morning the bottom booms were joined together for good.

It now required a good fall of the temperature to get the top booms connected, for the two halves of this girder had been set less high at starting, and there was now practically no camber in the bottom booms. But the weather remained obstinate and the temperature very high, and it was not until the morning of November 14 that the key-plates could be driven in and the final connection made. An episode, of which much has been made in the papers, occurred on this occasion, and the facts are simply as follows: After the wedges at the bottom ends had been drawn out and the key-plates driven in, a slight rise of temperature was indicated by the thermometer in the course of the morning, and orders were given to remove the bolts in the central joints of the connecting-ties and to light the furnaces. Whether the thermometer indicated wrongly or whether the cantilevers had not had time to fully expand under the rise of temperature, or whether a decrease of the same took place it is not now possible to prove, but when only about 36 of the turned steel bolts remained in the joints, and before the furnaces could get fairly started, the plate-ties sheared the remaining bolts and parted with a bang like a shot from a 38-ton gun. Something of a shake occurred in the cantilevers which was felt at the opposite ends, and caused some little commotion among the men. No mishap occurred, however, and nothing in the way of a fall of the girders took place as stated in the papers—simply the work of the furnaces and the task of knocking out 36 bolts was saved, and the girder swung in its rockers as freely as if it had been freed in the most natural manner.

And thus the Forth Bridge was completed—for the remaining work was simply to replace temporary connections by permanent ones, to rivet up those which were only bolted, and do the thousand and one things which always remain to be done after everything is said to be finished.

The thrilling portion of the story is done, and the novelist would wish to leave off with so dramatic an incident as that just told. But there are yet some details which belong to the history of the bridge, and which could not very well be left unrecorded.

Rivetting.

An early estimate has fixed the number of rivets in the Forth Bridge at 5,000,000, but this was evidently insufficient and the figure has risen to 6,500,000. It is, however, doubtful whether even this covers the total amount, for on the central or Inchgarvie pier, where an exact record of rivetting was kept, the number closed there amounts to near upon 2,700,000 alone, and a very large quantity of material was sent across from the shops and the field which had already been rivetted up, and such rivets are not included in the above total. The rivets varied as to diameter from 1¼ in. for the heavy tubes and the skewbacks down to ⅝ in. for the buckle-plates; and, as to length, from 11¼ in. (measured without the head) down to 1¼ in. The greatest thickness of plates rivetted together was 9 in., and this occurred in the top junctions at the head of the vertical columns on Inchgarvie—the least thickness was ½ in., in the flooring of the viaduct.

The various hydraulic rivetting machines, by which about one-half of the rivetting was done, have already been described in the places where they carried on their work, and need not be further enlarged upon here.

At the commencement, ordinary furnaces fired with coal were used for heating, but it soon became evident that these could not be taken on the outlying platforms owing to their weight, the weight of fuel, and last, though not least, to the danger of fire caused by hot ashes left on timber staging.

Various kinds of furnaces were designed and tried, all heated by oil, and in the end the difficulty was solved by turning the burner of an ordinary Lucigen lamp, in a somewhat modified form, into a small furnace and setting fire to it by a piece of burning waste drenched in oil. This was a tremendous advantage, for these little furnaces, though made of iron and brick-lined, weighed little more than half a ton, and could be handled and shifted about with the greatest ease. All they required was a small pipe-lead to supply compressed air, and a small tank with oil, and a crane would pick them up and put them into any place where they were most handy. A boy could work them and turn out 200 rivets an hour easily, all heated evenly to a bright yellow heat in perfect condition for the hydraulic machines, three or four of which were fully kept going by one of these little furnaces. They were taken inside the tubes, and the smoke, if care was taken in adjusting the burner, could not molest any one.

Larger furnaces were set up in No. 2 shed for heating angles and tees, and they were very successful owing to the regularity and evenness of the flame and the facility with which they could be lighted and kept up.

For the hand-rivetters in the struts and lattice-girders, ordinary small forges were in use, with bellows worked by a treadle or by the hand. But here also the oil-furnaces came in usefully, for not only were the rivets pre-heated in the furnace if one happened to be anywhere near, but the boys contrived to make a connection somewhere with the compressed air pipes, and thus obtained a constant blast for their forges and saved themselves the trouble of working the bellows.

In places where so large an amount of timber staging was required, and where a fire on such staging might have been accompanied by the most disastrous results to portions of the permanent work, such furnaces as above described are of inestimable value, for there is nothing left behind that could cause a fire after the men left work. As soon as the supply of air and oil are turned off all flame at once disappears, and in five minutes the inside is black and cold.

The ordinary small furnaces used in the tubes and on the staging were about 11 in. wide by 8 in. high and 4 ft. long on the inside, with two doors for charging and drawing of rivets. They consumed about two gallons of oil per hour, with which they could heat 200, and on an emergency 250 rivets per hour, or even 300, if of smaller size.

The actual size of this kind of furnace is however a matter regulated entirely by circumstances, and it is not possible to lay down hard and fast rules for their construction. The furnaces and fittings shown in the illustrations are:

A furnace for heating the ends of angle bars, tees, or narrow plates. (See Figs. 144 to 146.) An early form of oil furnace with grate at bottom to keep a body of glowing coal to assist combustion. This however is not necessary. (See Figs. 147 to 149.) The latest form of small rivet furnace as used on the stagings and inside the tubular members. (See Figs. 150 to 152.)

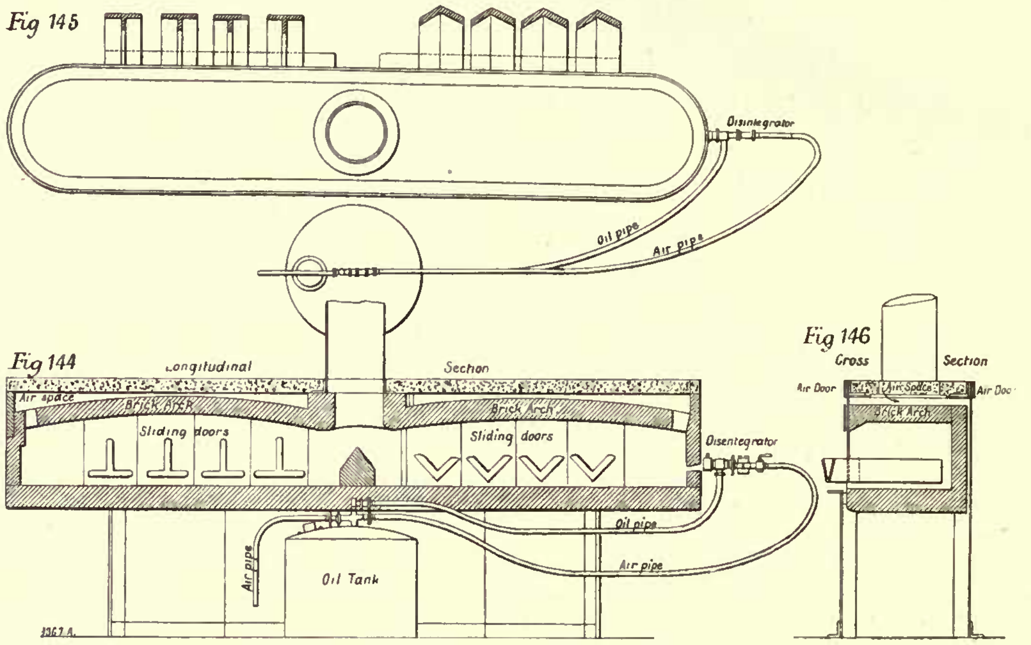
Figs. 153 and 154 show the disintegrator, or spray producer, the action of which explains itself. In its present form it is much simplified, and if any obstruction in the small jet occurs, it is easily cleared by screwing back the mouthpiece.

Temporary Work in Connection with the Erection.

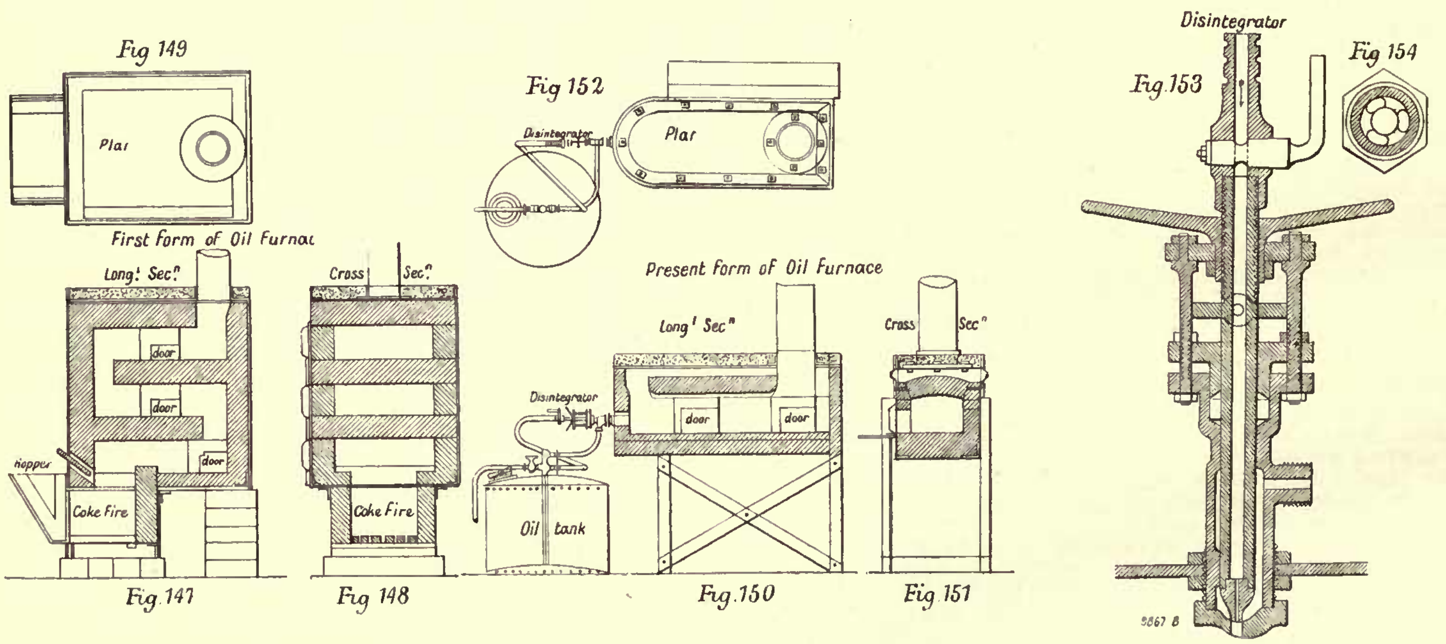
If the proud boast is perfectly justified that in building the two 1710 ft. spans across the Forth, and erecting the 11,600 tons of steel massed therein, without having placed a single stick of timber into the river, it is yet equally certain that this mode of erection entails an immense amount of auxiliary and temporary work, which is both costly and wasteful with regard to time. There were many days

and weeks lost through waiting for crossings or junctions to be built up and completed, and although much of this may be said to be due to the novel character of the work, yet it is a point which must not be lost sight of. Elsewhere, it has been stated that owing to the general batter of the sides of the structure, and owing to all of its members being out of the perpendicular, as well as the horizontal, they had a natural tendency to either fall together, or else apart, and in both cases apt to be both out of the right direction. Thus in building out a pair of struts or ties, so soon as a length of 30 to 40 ft. had been built, it became necessary to put up temporary girders to hold them apart or keep them together, and a large amount of dangerous work had to be done before a further section of work could be built. The members themselves, even when only bolted up, were often so stiff that hydraulic rams had to be used to force them apart or draw them together. In other cases wedges of hard wood and union screws were able to deal with them. In looking at the illustrations and plates showing various phases of the erection, this feature will immediately attract attention, and in many cases it must be difficult for any one except those conversant with the structure to distinguish between temporary and permanent work.

For reasons explained above, and easily understood, it was not possible to fix the wind-bracing so close up to the new work that temporary appliances could be dispensed with, and therefore an immense number of lattice-girders, some heavy, some light, had to be used to allow the permanent members to be corrected, and when corrected held in position. In the bottom members, especially near the piers, where they were some 120 ft. apart, centre to centre, the temporary girders naturally had to be very strong and heavy, but after the completion of three bays, timbers were in most cases sufficiently strong to take all resistance, and this much simplified matters, for timber is both light in weight and easy to cut and shape to requirements. Thus in the bottom members alone, at every vertical tie and at every junction, the necessary corrections required the placing of temporary struts and wire rope ties, and in most cases when finally fixing the horizontal wind-bracing girders, similar girders had to be placed to fix the position of the member. A repetition of this kind of work with every tie and strut, in bottom members and top members, at every vertical tie, and at every intersection, made up an amount of work of which no visible trace is left, yet which was as real in its day as any which helped to build up the mighty fabric.



OIL FURNACES FOR HEATING ANGLE BARS.



OIL FURNACES FOR HEATING RIVETS.

The Use of Wire Ropes.

Of all appliances in use during the erection none have given more unmixed satisfaction than steel wire ropes. It may be considered a rash guess, though the writer at any rate has no hesitation in making it, that the list of accidents would have been doubled at least, and a great deal more time and money expended, but for the absolutely reliable character of this article, and for its manifold uses.

In the first instance there were nearly a score of cages or hoists for the raising of men and materials to the different levels at which work was carried on, and these were going continuously day and night for several years, and there is not a single case on record of a rope having given way without having given ample warning. At first the pulleys over which the ropes passed were rather small in diameter, and the result of continuous running was that single wires commenced to give way, but with a crackling noise which soon became known to the attendant at the hoist. With the introduction of pulleys of 3 ft. 6 in. in diameter, and guide pulleys not smaller than 18 in., and having the bottom of the grooved pulleys laid with hard wood, the ropes lasted three to four times as long, that is from nine to twelve months. Even when taken off the hoists, moreover, they were quite good enough to act as guide ropes to the cages, or to support steady weights when used as pennants, or as temporary ties between the various members of the structure.

All cranes used upon the erection had their chains taken off by degrees, and were supplied with wire ropes instead, which did the work more quietly and with far more safety and reliability. Still more useful were the ropes when portions of overhanging girders or other members had to be temporarily suspended from other portions already fixed. In these cases, by means of union screws attached between the girders and the ropes, the former could be raised and lowered at will and held in position until a joint with other portions of the work was made. Thus in the central towers, once they were completed, everything within the area could be suspended, and thus the internal viaduct was built in the easiest manner possible, every length in succession being held up until the girder was complete and able to carry itself. And thus in the same manner while building out the bottom members in cantilevers, the vertical ties and struts, and later on the wind bracings, a few wire ropes attached to the upper members, as far back as necessary to obtain a fixed hold, held up—and if required drew up—the overhanging ends to any desired position.

It is only necessary to call attention to the weight of these ropes in comparison with that of chain cables and hemp ropes of equal strength, to see at once the great advantages which the use of these ropes offered for the particular kind of work which had to be done at the bridge.

Circumference of Wire Rope.	Weight per Fathom.		
	Wire Rope.	Cable Chain.	Hemp Rope.
4 in.	12 lb.	54 lb.	33 lb.
3 ,,	7 ,,	30 ,,	19 ,,
$2\frac{1}{4}$,,	$3\frac{3}{4}$,,	21 ,,	$11\frac{1}{4}$,,

In all cases mentioned here the wire rope had a higher breaking stress than the other two.

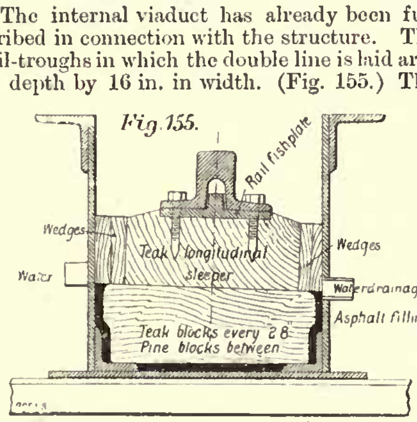
Facility of attachment was also a very good feature; for they could be tied like an ordinary rope, or else have the end fixed round a common thimble or deadeye, and be used with shackles. Nearly all the small stages which had been passed up and down or along the members were hung by short pennants made of wire rope.

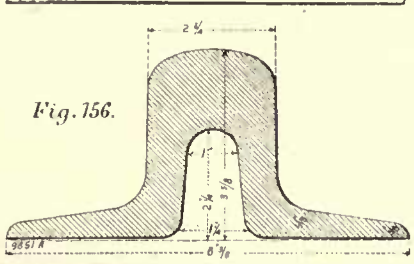
Finally, they could be slung alongside or across the structure, and by means of running snatch-blocks every place made accessible to the men, or they could be used for raising material by means of single whips worked over a steam-winch barrel. The employment of wire ropes for this purpose is well shown in the large illustration on Plate X. and Plate XV.

The sizes used here mainly were the $2\frac{3}{4}$ in. or $\frac{7}{8}$ in. diameter, the $2\frac{1}{4}$ in. or $\frac{3}{4}$ in. diameter, and the $1\frac{7}{8}$ in. or $\frac{5}{8}$ in. diameter were used on cranes or for single whips upon steam winches. For special purposes $3\frac{1}{2}$-in. and 4-in. ropes were used, and for the service of men's cages and hoists the 3 in. or 1 in. diameter. The tests for the latter gave a breaking stress of 26 tons to 28 tons, while nothing heavier than 3 tons in the case of material and 35 cwt. in the case of a cage full of men were ever put upon them.

The Permanent Way.

The internal viaduct has already been fully described in connection with the structure. The four rail-troughs in which the double line is laid are 18 in. in depth by 16 in. in width. (Fig. 155.) They are





asphalted in the bottom to the level of the heel in the angle-bars, in order to make a water-tight bottom. Upon this bottom are laid transversely, about every 2 ft. 8 in. apart, blocks of teak about 5 in. square. Between these blocks the spaces are filled in with blocks of creosoted pine, all set about $\frac{1}{8}$ in. to $\frac{1}{4}$ in. apart, and the whole is then filled up to level with a mixture of pitch and tar and black oil, which quickly sets hard.

Stiffening plates of steel, about 6 in. wide and $\frac{3}{8}$ in. thick, are rivetted in about every 14 ft., and project about 2 in. above the teak blocks. All blocks are cut with an inward slope towards the centre of each line of about $\frac{1}{2}$ in. to the foot.

The whole mass of blocks and filling, which completely seals the lower portion of the trough, are now dressed for the reception of the longitudinal sleepers, which are about 12 in. by $5\frac{1}{4}$ in., and also of teakwood. They are cut in lengths which are multiples of the 2 ft. 8 in. distance of the transverse blocks, and are notched where the plate-stiffeners occur. Play to the extent of $\frac{3}{16}$ in. to $\frac{1}{4}$ in. is left between sleepers lengthwise.

Through the sleepers holes are bored every 2 ft. or 3 ft., and $\frac{3}{4}$-in. pins driven down into the blocks The sleepers are kept in position transversely by wedge-shaped blocks of teakwood. The upper faces of the long sleepers are dressed to receive the rails of "bridge" section, the heaviest yet rolled weighing 120 lb. to the lineal yard. A section of the rail is shown in Fig. 156. The rails are joined by a horizontal fish-plate underlying the flanges, and sunk into the sleepers with a projection entering into the hollow of the rail. The rails are screwed down by $\frac{3}{4}$-in. wood screws with hexagon heads. The total weight of rails, fish-plates, bolts, expansion joints, &c., for the double line of rails across the bridge and viaducts, is over 600 tons.

The rail-troughs are drained of water through holes drilled into the sides every few feet at the level of the top of the tranverse blocking. In the floor of buckle-plates between the four troughs holes are placed to let the water through, these spaces being made up with asphalt mixture in such manner as to lead all the water to the outlets.

The footpaths on each side of the double line are made up like ordinary pavements, on the system followed by the Seyssel Asphalt Company, the slope being such as to lead all water to the outer sides.

Expansion Joints in Rails.

These are all arranged on the same principle, though of different lengths. In the approach viaduct span, and at the fixed ends of the central girders, the movements are so insignificant that a very short rail-joint suffices to regulate the lateral displacement of the points due to contraction; but, at the sliding ends of the central girders, where provision is made for a longitudinal movement of two feet, and at the ends of the fixed cantilevers, where half that length is provided, the arrangement is somewhat more complicated. Without going more into detail, it will suffice to say that the long rail-tongue is made an absolute fixture to the rail-trough in which its uncut end rests. Its pointed end, cut at an angle of 1 in 63, projects into the opposite trough and rests on a plate fixed therein, laying up close to the backing rail, which is bent away at an angle of 1 in 63 from the point of the tongue. The outside of the flange of the rail-tongue is cut in long steps at the same angle of 1 in 63, and is held down by draw-washers to the plate, which forms one piece with the backing-rail, but in such manner that it can slide in and out with the expansion and contraction. In doing so, however, by means of the sloping steps it draws the lower plate and with it the backing-rail always close up to the joint, which thus retains its position relative to the centre line of the bridge and thus keeps the gauge correct. The contrivance is very ingenious and unfailing in its action. (See Fig. 127.) The wind fence on each side of the viaduct is 4 ft. 6 in. high, and of close lattice work, and it is crowned by a handsome teak handrail of substantial appearance.

Painting.

All plates, bars, angles, and other parts belonging to the superstructure, received as soon as they had passed through the shops or yards a thorough scraping with steel scrapers and steel wire brushes, and afterwards a coat of boiled linseed oil applied as hot as possible. As soon after erection upon the structure as could conveniently be done, and in many cases also before they were put up, they received a coat of red lead paint, and subsequently a second coat of red lead. The paint finally decided upon for the bridge is an oxide of iron paint, of which two coats are applied over the two coats of red lead already laid. The first is called a priming coat of dark chocolate brown; the last is a finishing coat of a bright Indian or Persian red, which, however, darkens considerably in a short time. Four different kinds of paint are used, all, however, of the same composition, if of different makers.

At Fife: Craig and Rose's.
At Inchgarvie: Calley's Torbay.
At Queensferry: Carson's.
For central girders: Wolston's Torbay.

The above are for outside painting only, the inside of the tubular members receiving one coat of red and two coats of white lead paint.

It is calculated that inside and out, the amount of surface to be painted is equal to 145 acres.

Asphalting.

The batter given to the sides of the structure brings with it one disadvantage, namely, that one-half of each lattice-girder flange forms with the vertical web a recess in which rain-water can lie and cause rusting. To prevent this, all places so situated that the water cannot of its own accord drain away are filled with asphalt-concrete—that is, a mixture of asphalt, pitch, tar, and coarse gravel—to such an extent that all water will run off by gravity. Where this is not possible, or would lead to too much weight being put on, holes are drilled, and the asphalt so laid that the water is drained to them and away through them. The top members in central towers, all horizontal bracing girders, and all recesses in top and bottom junctions, are done in this way.

The whole of the inside of the skewbacks, except where the nuts of the foundation-bolts are situated, are also dealt with in the same manner, and the same at the bottoms of the vertical columns, the diagonal columns, and the struts in cantilevers; and in all cases pipes are fixed to lead the water to the outside. By this means it is hoped to prevent all rusting in the places where access for constant and thorough inspection, is not easily to be had.

The Workmen.

Taking them as a whole, it must be freely acknowledged that the workmen employed upon the bridge have not, to any material extent, added to the troubles and anxieties attendant upon such a work. Black sheep are found everywhere, and of the doings of such a tolerably lively account might easily be presented. Many of them—hundreds of them—were mere birds of passage, who arrived on the tramp, worked for a week or two, and passed on again to other parts, bringing a pair of hands with them and taking them away again, and having in the mean time made extremely little use of them except for the purpose of lifting the Saturday pay packet and wiping their mouths at the pothouse; many others also, who, too clean-shaven and too closely-cropped as to hair, vainly tried to deceive any one as to the character of the hotel they were last staying at, or to invent a plausible account of the big job which they had just left completed. The paddle-steamer, which carried the men across the river morning and night, during the day made hourly trips to the north shore and back for the service of the works and for the accommodation of visitors. Before many months had gone by it was known all over the country to every tramp that a free passage could be had for the stepping on board the boat, and the number of men who, when on the south side, were invariably asking for a job on the north side, and *vice versâ*, increased at such an alarming rate that steps had to be taken to stop the nuisance.

But apart from these, it is no exaggeration to say that no one need desire to have to do with a more civil or well-behaved lot of men, always ready to oblige, always ready to go where they were told to go, cheerfully obeying orders to change from one place to another, and, above all things, ready to help others in misfortune, not with advice but with hands and purses. Nor was there any difference in that respect on account of nationality; Scotch, English, and Irish were about equally represented as to numbers, and though the latter furnished very few skilled hands, they were mostly very hard workers and very conscientious and reliable men.

For the sinking of the caissons a number of foreign workmen were employed for a short time. and it is rather a curious coincidence that, as foreign workmen did some of the earliest work in connection with the bridge, so now again a number of foreign men are employed upon some of the last work—namely, the laying of the asphalt pavement along the footpaths of the permanent way, which is done under a sub-contract by the Seyssel Asphalt Company.

Several strikes occurred during the building of the bridge, most of them brought about, not by the men themselves, but by organised committees in connection with various Trades Unions and their disputes with employers in other parts of Scotland. The causes were often trivial enough, such as the discharge from the works of some idle scamp with an inordinate allowance of the gift of the gab, and whose demand to be reinstated in his dignity at twenty-two shillings per week, caused an immense amount of useless suffering to scores of his fellow-workmen, and more still to their families, and a proportionate increase in the takings of the neighbouring whisky shops.

The principal strike took place early in June, 1887, and was brought about through an accident, caused entirely by the carelessness of a few men. A movable stage for rivetters, consisting of two girders about 110 ft. long, disposed on either side of the vertical columns, was hung by wire ropes from winches worked by worm and wormwheel placed above. The stage served for rivetting the wind-bracings between the columns, and was made good by planking across the two girders in any place required. When one section had been done the stage was raised to the next section, and while

this was being done one of the girders fouled a piece of timber left in the girders. This was not noticed, and in spite of the resistance the men kept forcing at the handles of the winches until one of the wheels broke, and the whole stage rattled down, carrying with it some other staging on which some men were working. Two men and a boy were killed, and two more wounded, and before the real facts were known the usual agitators quickly organised a strike, demanding an increase of a penny per hour all round, equal to a rise of from 15 to 20 per cent. in their wages, on account of the dangerous nature of their work. As might have been expected the principal spouters at the meetings held during the next following few days were men who worked in the yards away from all danger, or who did not work at all, and after holding out for a week most of the strikers were glad to be allowed to come back.

That accidents were frequent no one who can form an idea of the nature of the work upon such a structure need be told, but it is equally true that fully three-fourths of all more serious accidents were due entirely to what may strictly be called preventible causes. If any charge can be brought against the workmen, or at any rate a large proportion of their number, it is that of utter indifference or carelessness with regard to danger of causing injuries or death to one another. Not that in cases of sudden accident men would have hesitated to risk limb or life for the sake of helping. On the contrary, at such times the most heroic efforts were made to succour those in need; but in the every-day work—with that fatal familiarity that is said to breed contempt—while working on stages which could hardly be made large enough or strong enough to hold the litter of tools and rubbish which they constantly gathered, they were throwing about hammers and drifts and chisels, and pieces of wood, which in a moment were over the side, and tumbled down upon may be three or four other tiers of staging, where men were engaged upon their work. Special gangs of men were organised to clear all these things away, and endless warnings and entreaties were given, but to no avail, and it needed the sight of a wounded and mangled fellow-creature, or his bloody corpse, to bring home to them the seriousness of the situation and the advisability of stooping to put down a tool instead of throwing it carelessly away.

In the summer of 1883 a Sick and Accident Club was started upon the works. The membership was compulsory for all employed by the contractors, and the amount of contribution to the funds was one hour's pay per week, the maximum contribution being 8d. per week. Members were entitled to medical advice and medicines, bandages, &c., for themselves, and medical advice for their wives and families, but no medicines, and, in addition, if unable to work, an allowance from the funds proportionate to the weekly contribution made. This aliment ranged from 9s. up to 12s. per week. The funerals of members were also paid within certain limits, and in cases of death or permanent disablement by accident or injury sustained on the works, grants were made to widows, wives, and children. The contractors contributed a sum of 200*l.* yearly to the Club, and gave a good deal of other substantial assistance. The Club proved a great boon to the men, and more still to their wives and children, inasmuch as they got a great deal more care and attention than they otherwise would have been likely to experience. Special medical men were appointed at Dunfermline, North Queensferry, Leith, Edinburgh, Kirkliston, and South Queensferry. An ambulance waggon was provided, and temporary hospitals with every appliance needed in case of accident were established upon all three main centres.

The amount contributed by the members of the Club in the year 1888, when the greatest number was employed, was 4096*l.*, which, with donations, the contributions by the firm, &c., came up to 4546*l.* Out of this sum sick allowances were paid out to the amount of 1621*l.*; accident allowances, 729*l.*; funeral expenses, 143*l.*; widows' allowances, 176*l.*; donation to the Royal Infirmary, 100*l.*; and the rest being medical fees and other expenses. The attendances by the medical staff amounted to over 26,000 in the year. On the average 99 men were receiving aliment from the Club every week. Of accidents between July, 1883, and Christmas, 1889, when the Club ceased to exist, there had occurred 57 fatal, 106 which required removal to the infirmary in Edinburgh (in which number, however, some of the fatal accidents are included, the men having died after admission), and 518 minor accidents, which required, however, the attendance of a medical man.

Apart from the benefits of this Club, however, the men's welfare was looked after in every respect. While working in the foundations boots and waterproofs were provided for them free of charge. Later on, during the erection, they were given thick woollen jackets, as well as overalls and waterproof suits, and although a nominal charge was made for some of these in order to check the carelessness and bad treatment of these things, it was rarely enforced against a careful and deserving man.

Large shelters and dining rooms were provided for them, with stoves and men in charge to heat their food for them, and these were not only on deck but on the top of the central towers, at the level of the viaduct and right out near the very ends of the cantilevers. Here the men not only could take their meals in warmth and comfort, but they could retire also in case of heavy showers or sudden storms.

In cases of accidents not caused by the men's own fault, the full wages were as a rule paid by the contractors until the injured man was able to return to work, or unless an action was raised against the contractors.

Every care was also taken and no expense was spared to make good and secure staging for the workmen, and to construct gangways and roomy staircases to all places where work was carried on.

The wages paid to all classes of workmen were as a whole rather above the average, and as by far the greatest amount of outside work was done by the piece, a skilful and steady workman was enabled to make double and treble his ordinary time wages if he applied his abilities and energies in the right direction.

Some curious aspects of the labour question developed themselves in connection with piecework. The hand-rivetters worked invariably in squads of four, namely, two rivetters, one holder-up, and one rivet-heater, generally a boy or lad. Now it is easy to see that the skill or the want of it in the last functionary was of great influence upon the number of rivets put in during a day's work, and consequently a sharp handy lad was worth a good wage, and as a rule he knew it. Rivetters are not generally very steady, but often lose a day or two, in which case one or more of the squad are liable to enforced idleness. After some little discussion among themselves, these rivet-heating boys stood out for a fixed minimum sum, 20s. to 24s. per week, and this had to be paid whether the squad worked or not. This did not of course affect the employers, for in piecework the head man of the squad was paid so much per 100 rivets, and he had to settle with the other members of his squad. In another sense it is said the boy is father to the man; here the boy was master of several men. The wages were paid weekly.

The number of men employed varied somewhat with the nature of the work to be done, and naturally also with the seasons, as in some instances it was next to impossible to work during the night. In the spring of 1887 the number had risen to 3200, and rose to over 4100 in September of the same year. After the lifting platforms were up to full height in the central towers the number fell again during the winter months to about 2900, but rose again as the summer advanced. The largest number employed at one time was 4600. From January, 1889, the numbers gradually decreased, and in January, 1890, the average was 1200, and in February, 1000. A large proportion of these hands are platelayers working upon the permanent way, and painters and their labourers. The removal of the staging round the piers and the landing jetties, and the disposal of the plant, as well as the restoration of the ground occupied by the workshops and yards, for agricultural purposes, will occupy a goodly number of hands for some months to come yet.

The Railway Connections.

The railway works now in course of construction, and more or less directly connected with the Forth Bridge, are extensive and important as regards the amount of heavy work they entail. Of these only two lines are being constructed by the Forth Bridge Railway Company, the remainder being done by the North British Railway Company. The two lines are the south approach and the north approach railways, the former extending from the south arches of the bridge to a junction with the North British Railway at Dalmeny, the latter from the north arches of the bridge to a junction with the North British Railway at Inverkeithing.

The engineers for the approach railways are Messrs. Sir John Fowler and Baker, and the contractors Messrs. W. Arrol and Co. The further works are :

On the south side :

1. A line from Dalmeny Junction in a more direct line to a junction with the North British Railway at Corstorphine Station, outside Edinburgh. Total length, 6 miles. Engineer, Mr. James Carswell. Contractor, Mr. W. Arrol.

2. A line from a point between Dalmeny Junction and the Forth Bridge, to a junction with the North British Railway at Winchburgh. Length, 4½ miles. Engineer and contractor the same as for Corstorphine line.

On the north side :

3. A line from Inverkeithing to Burntisland to join the ordinary route from Edinburgh to Dundee, *viâ* Granton and Burntisland. Total length, 7 miles 3 chains. Engineer, Mr. W. R. Galbraith. Contractors, Messrs. John Waddel and Sons.

4. Widening and doubling of a line from Inverkeithing to Townhill Junction, both on the North British system. Length, 5 miles 24 chains. Engineer, Mr. James Carswell. Contractors, Messrs. G. and R. Cousin.

5. A new loop line from Cowdenbeath to Kelty, both on the North British system. Length, 2 miles 69 chains. Engineer, Mr. W. R. Galbraith. Contractors, Messrs. Charles Brand and Son.

6. Widening and doubling of a line from Kelty to Mawcarse, North British system. Length, 10 miles 3 chains. Engineer, Mr. James Carswell. Contractor, Mr. John Best.

7. A line from Mawcarse through Glen Farg, to a junction with the Bridge of Earn station, North British system. Engineer, Mr. W. R. Galbraith. Contractors, Messrs. Charles Brand and Son.

A glance at the map of Scotland will show that through these new lines the North British Railway obtains access to both the east and west of the northern parts. To Dundee and Aberdeen, *viâ* Inverkeithing, Burntisland and the Tay Bridge. To Perth and the districts served by the Highland Railway, *viâ* Inverkeithing, Kinross, Glen Farg, and Bridge of Earn. The line from the Forth Bridge to Winchburgh opens a direct route to and from Glasgow and the west coast without touching Edinburgh. The following is the estimated cost of connecting railways now under construction on the North British system:

	£
South of the Forth :	
Dalmeny to Winchburg	56,000
,, to Corstorphine	78,000
North of the Forth:	
Inverkeithing to Burntisland ...	213,000
New lines, and widening and doubling existing lines between Inverkeithing and Mawcarse, also Glen Farg line from Marcarse to Bridge of Earn	435,000
Total estimated cost	£,774,000

The following Table of comparative distances between Edinburgh and four towns north of the Forth, both by Caledonian and North British, may be of interest:—

—	Length in Miles.	
	North British.	Caledonian.
Edinburgh to Aberdeen, *viâ* Forth and Tay Bridges ...	130	159
Edinburgh to Dundee, *viâ* Forth and Tay Bridges ...	59	90
Edinburgh to Perth, *viâ* Forth Bridge	48	69
Edinburgh to Montrose, *viâ* Forth and Tay Bridges ...	90	123

It is not improbable that arrangements can be made to get the following results as regards train service between London and the North. London to Perth, 9¾ hours. London to Dundee, 10½ hours. London to Aberdeen, 12¼ hours.

The South Approach Railway.

This line has a total length of 58 chains, and passes through a cutting about 20 ft. on the average in depth, through soil and clay, and strata of freestone, intermixed with coal and shale.

At about 10 chains from the bridge the new Forth Bridge Station is situated. At 45 chains the line to Winchburgh branches off to the west with a sharp curve.

The building of the Forth Bridge Station, and the widening of cutting, bridges, and embankments not at first contemplated, will bring up the total cost to about 20,000*l.* The contract will probably not be finished until the end of April.

The North Approach Railway.

This line is nearly two miles in length, and commences with an embankment at the north end of the bridge. The embankment is 34 ft. in depth at the abutment of the masonry arches, and continues for a length of 14 chains, when cutting No. 1 commences. This cutting is through whinstone, and is over 600 yards long, with an average height of 80 ft. The work here was commenced by driving a toplift from both ends at about 40 ft. above formations, and at the same time bottom gullets from the south end and the north end. The material excavated was run down an incline, worked by gravity in the ordinary way, and deposited to form No. 2 bank. The excavation made in the top-lift proved the rock to be of such a nature that an open cutting at the great depth would not have been compatible with safety to the traffic, and it was decided to form a covered way for the portions already excavated and to tunnel the remainder. Accordingly, shafts were sunk in two places, and headings were driven from them in each direction. The tunnelled portions are lined with side walls of roughly dressed whinstone and rubble backing, while the roof is of brick. The covered way has side walls and roof both of whinstone masonry. Starting from the south end of this cutting there are 189 yards of covered way, 229 yards of tunnel, and 154 yards of covered way, at the end of which the cutting terminates and bank No. 2 commences. This is 11 chains in length, and is followed by a cutting through whinstone 11 chains in length and, on the average, 50 ft. in depth. Another embankment follows, gradually deepening and leading to a viaduct crossing the North British Railway and the public high road, and by another bank the outskirts of Inverkeithing are reached.

The viaduct consists of masonry abutments in the form of eliptical arches of 57 ft. span at either end and four spans of steel girders of 100 ft. span each. The girders rest on masonry piers set at an angle of 25 deg. to the centre line, and the whole viaduct is on a curve of 40 chains radius with a gradient of 1 in 70.

At the north abutment of this viaduct the bank is 85 ft. in height, but, situated on rising ground, rapidly falls away.

At $1\frac{1}{2}$ miles from starting another cutting through whinstone commences, this extending for 6 chains, followed by a tunnel 378 yards in length under the town of Inverkeithing. Finally the line terminates in a junction with the North British Railway at Inverkeithing.

The last-mentioned tunnel is also on a curve of 40 chains radius with a gradient of 1 in 70, and was excavated by means of headings driven from each end. The enlargement to full size was principally made from the south end of the tunnel, as the material was required at that end for the filling up of the banks. This tunnel is lined with masonry side walls, and a brick roof.

Apart from the heavy cutting and tunnelling work, the greatest difficulty in this contract was caused by a bog through which bank No. 2 had to be carried. After some quantity of spoil had been tipped from the north end of No. 1 cutting, the weight of this material commenced to force up the ground in front, and this to such an extent as to displace the public high-road running to the south-west side of the bank, carrying this road some 60 ft. out of its course and altering the gradients materially. There was at one time a fear that it would displace the North British Railway line between North Queensferry and Inverkeithing as well, but fortunately it stopped short of this. There is in this bank an excess of 69,000 cubic yards over and above the estimated quantity of 115,600 cubic yards, and to obtain the necessary quantity of spoil the east side of No. 2 cutting was enlarged to the necessary extent.

Geologists will have it that this is the site of an extinct volcano, but it will probably be best to leave this question to be settled by geologists.

In the excavation of tunnels and cutting, pneumatic drills were generally used with good results. The explosives used were both dynamite and ordinary blasting powder.

The total rock excavation amounted to 341,500 cubic yards in the solid.

The filling in the banks is as follows:

Bank No. 1	33,400	cubic yards.	
No. 2	115,600	,,	(original estimate)
,,	69,000	,,	(excess)
No. 3	198,100	,,	
Masonry	24,850	,,	
Ballast	13,350	,,	
Filling	1,000	,,	
Total	455,300	cubic yards.	

The total weight of steelwork in the viaduct and road bridges is 460 tons for the former and 190 tons for the latter—total, 650 tons.

The whole north approach line, from the abutment of the bridge to Inverkeithing, is on a gradient of 1 in 70, except at one point, where it is level for about 100 yards.

The sum for this contract was 88,678*l.*, increased through extra work by 18,000*l.*, or a total of 106,678*l.*—equal to something over 56,000*l.* per mile.

A new station has been built at Inverkeithing. At present there is no station between this and the Forth Bridge Station on the south side.

The writer wishes to express his indebtedness to Mr. Louis Neville, the contractors' engineer for the approach railways, who furnished the above particulars.

Weight of the Superstructure.

The subjoined tabular statement will give some idea of the amount of steel distributed over the main supports.

TABLE No. XI.—Quantities of Steel used in Main Spans.

Description of Parts.	Fife.	Inchgarvie.	Queensferry.	Total.
	Tons Cwt.	Tons Cwt.	Tons Cwt.	Tons Cwt.
3 Central towers, including bedplates ...	4815 16	7036	4815 16	16,667 12
6 Cantilevers	1 fixed 1 free	2 free	1 fixed 1 free	
Bay 1	4235 4	4312 12	4235 4	12,783
,, 2	2626 2	2658 12	2626 2	7910 16
,, 3	1764 6	1724 16	1764 6	5253 8
,, 4	1034 3	1009 16	1034 3	3078 2
,, 5	665 18	620 4	665 18	1952
,, 6	490 2	423 12	490 2	1403 16
2 Central girders	410 15	821 10	410 15	1643
Rocking-posts and steel castings... ...	51 9	51 9	51 9	154 7
Ladders in tubular members	36	40	36	112
Totals	16,129 15	18,698 11	16,129 15	50,958 1

Weight of a fixed cantilever: 5441 tons.

,, ,, free cantilever: 5375 tons.

,, ,, 1710 ft. span: 11,571 tons 10 cwt.

,, ,, cantilever bridge per foot run: 9 tons 11 cwt.

Table No. XII. on the next page shows the quantities of steel erected and bolted up and rivetted during the years 1887, 1888, and 1889, month by month. These quantities apply to the three main piers of the cantilever bridge only.

The total cost of the foundations of the Forth Bridge may be roughly put down as nearing 800,000*l.*; and in connection with this expenditure it is necessary to mention the name of Mr. P. W. Meik, who acted as resident engineer for, and as representative of, Messrs. Sir John Fowler and Baker from the commencement in 1883 until the completion of the masonry piers in 1886, and of whose unfailing tact and courtesy his many friends retain the liveliest remembrance.

Another name should be added here, that of Mr. William Gray, who from start to finish had charge of all excavation and masonry work, besides other duties of the most multifarious character, and of whom it may be truly said that, day or night, early or late, no one would ever call upon him and find him unwilling to do what was wanted.

The total expenditure by the Forth Bridge Company upon construction has been as follows. The figures are approximate amounts as far as expenditure year by year is concerned, but the total amounts are correct and authentic.

	For half-year ending	
These amounts include the expenditure for the construction of the north and south approach railways, but nothing for the connecting lines.		£
	December 31, 1882	7000
	June 30, 1883	42,800
	December 31, 1883	57,000
	June 30, 1884	119,000
	December 31, 1884	218,200
	June 30, 1885	231,000
	December 31, 1885	216,000
	June 30, 1886	188,000
	December 31, 1886	253,500
	June 30, 1887	240,000
	December 31, 1887	243,000
	June 30, 1888	195,700
	December 31, 1888	218,000
	June 30, 1889	182,000
	December 31, 1889	138,000
	Total	2,519,200

Add to this the amount expended in connection with Sir Thomas Bouch's suspension bridge (including all parliamentary expenses)	250,000
	2,799,200
Parliamentary expenses in connection with cantilever bridge, engineering expenses, interest during construction, &c.	378,006
Total expenditure to January 1, 1890	3,177,206

It is estimated that a further sum of 50,000*l.* will be required to complete the structure, the painting included.

The sale of plant is expected to realise fully 120,000*l.*

For the erection alone of the Fife, Inchgarvie, and Queensferry Piers, that is, everything on top of the circular granite piers which may be strictly called the superstructure, the amount of wages paid including salaries of officials in charge of the piers, amounted up to November 30, 1889, to a total sum of 344,810*l.*; the total amount of steel put up and rivetted up to that date being 50,064 tons. The cost of labour for that work is therefore 6*l.* 17*s.* 9*d.* per ton erected and rivetted up.

The total amount of wages and salaries paid on the works up to January 1, 1890, was 1,045,000*l.*

The Forth Bridge Railway Company.

The agreements between the four companies which guarantee the interest on capital, provide that the directorate of the Forth Bridge Railway Company should consist of the chairman and vice-chairman of each of the four interested companies, and of two directors elected by the general body of shareholders. The chair of the Forth Bridge directorate is held in rotation by the four chairmen of the guaranteeing companies, the term of office being twelve months. The representation at present is as follows:—

Mr. M. W. Thompson, chairman, and Mr. W. Unwin Heygate, Midland Railway Company.

Lord Colville, of Culross, and Lord Hindlip, Great Northern Railway Company.

Mr. John Dent-Dent, deputy chairman, and Sir Matthew White Ridley, Bart., North-Eastern Railway Company.

The Marquis of Tweeddale and the Earl of Elgin and Kincardine, North British Railway Company.

TABLE No. XII.—Progress of the Erection of the Superstructure of the Forth Bridge, 1887 to 1889.

Month.	1887. Erected and Bolted up.	1887. Rivetted.	1888. Erected and Bolted up.	1888. Rivetted.	1889. Erected and Bolted up.	1889. Rivetted.
	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.
January	793	521	1045	1090	1159	1922
February	652	716	1055	1149	1126	1647
March	922	817	653	742	1098	1499
April	1242	984	1703	1382	1061	1565
May	1122	819	1910	1316	1556	1991
June	1099	500	2351	1760	1047	1595
July	1180	973	1923	1341	593	1080
August	1151	1045	1929	1742	449	891
September	1050	876	2089	2104	897	906
October	1285	938	1638	2397	626	799
November	1561	1235	873	1402	265	515
December...	959	1112	1598	1948	111	449
	13,016	10,536	18,767	18,379	9988	14,859

TABLE No. XIII.—Summary of Progress in Erecting Superstructure of the Forth Bridge.

—	Erected and Bolted up.	Rivetted.
	Tons.	Tons.
Up to the January 1, 1886, there had been put together and rivetted	512	512
During the year 1886	8284	6227
,, ,, 1887	13,016	10,536
,, ,, 1888	18,767	18,379
,, ,, 1889	9988	14,859
Total to January 1, 1890	50,567	50,513

There remained, therefore, on January 1, 1890, still to do—391 tons to erect and bolt up, 445 tons to rivet.

Mr. Spencer Brunton and Mr. James Hall Renton, elected by the shareholders.

The secretary of the company is Mr. G. B. Wieland, who is also secretary of the North British Railway Company.

The engineers to the company are Sir John Fowler, K.C.M.G., C.E., and Mr. Benjamin Baker, C.E.

The contractors for the bridge are :—Sir Thomas S. Tancred, Bart. ; Mr. W. Arrol ; Mr. T. H. Falkiner ; and Mr. Joseph Phillips.

The contractors for the south and north approach railways are: Mr. W. Arrol ; Mr. T. H. Falkiner ; and Mr. Joseph Phillips.

On the staff of Messrs. Sir John Fowler and Baker were the following : Mr. Allen Stewart ; Mr. P. W. Meik, resident engineer from 1883 to 1886 ; Mr. F. E. Cooper, resident engineer from 1886 to 1890 ; and a number of assistants.

On the contractor's staff were : Mr. Thomas Scott, manager ; Mr. W. Westhofen, who was specially engaged on the works at Inchgarvie ; Mr. A. S. Biggart, in charge of drawing offices, shops and yards ; and a number of others.

The Visitors.

Their name is simply legion, for from beginning to end there has been an extraordinary amount of interest shown in this work by all classes of society. From the visit of their Royal Highnesses the Prince and Princess of Wales, August 23, 1884, down to the present day, hardly a week has passed without bringing some person of rank or distinction. Dom Pedro of Brazil, the Kings of Saxony and of Belgium, and the Shah of Shahs, head this list, which includes, without exaggeration at any rate one-tenth of all people distinguished by rank or by scientific or social attainments.

As in most other matters ladies were to the fore, pluckily climbing into every nook and corner where anything interesting might be seen or learned, up the hoists and down the stairs and ladders, and frequently leaving the members of the so-called stronger sex far behind. It is needless to say that under such circumstances the duties of those called upon to guide the fair visitors were of the most agreeable.

The Preliminary Tests.

On January 21, 1890, two trains entered upon the bridge, side by side from the south end, and composed as follows :—Each train had two locomotives of 72 tons each at the head, followed by 50 waggons weighing fully 13 tons 10 cwt. each, and one engine at the rear of 72 tons. Total weight of each train, 900 tons ; total weight on bridge, 1800 tons ; total length of train when close-buffered, 998 ft. 6 in. ; the same, when open or loose-buffered, 1040 ft.

The train was moved slowly until the two engines in front were three-quarters through the central girder connecting Inchgarvie with Queensferry, the rear engine being about the centre of the Queensferry Tower. This is considered the most unfavourable load for the Queensferry north cantilever. In that position the following observations were made : The vertical columns of the central tower in Queensferry were drawn north to the extent of 1$\frac{3}{8}$ in. The end of the Queensferry north cantilever deflected 5 in., the end of the Inchgarvie south cantilever deflected 1$\frac{5}{8}$ in., the end of the Queensferry south cantilever (at that time not fully loaded by nearly 200 tons) rose to the full amount of play existing, namely, $\frac{3}{16}$ of an inch. The Queensferry south cantilever in itself took an upward deflection of about 1$\frac{1}{8}$ in.

The train then moved forward until the two front engines of the trains were three-quarters through the north central girder, the most unfavourable condition of loading for the Inchgarvie north cantilever. In this position the vertical columns of the Inchgarvie central tower were drawn north to the extent of 1$\frac{1}{4}$ in., while the Fife central tower was drawn $\frac{1}{2}$ in. to the south. The vertical downward deflection of the end of the Inchgarvie north cantilever was 6$\frac{7}{8}$ in., and the same for the end of the Fife south cantilever was 2$\frac{1}{2}$ in., while the end of the Inchgarvie south cantilever rose to the extent of 3$\frac{1}{2}$ in.

It is not necessary in the face of further trials by the Board of Trade, to say more than that all these movements were well within the calculated amounts.

THE ENGINEERS AND CONTRACTORS OF THE FORTH BRIDGE.

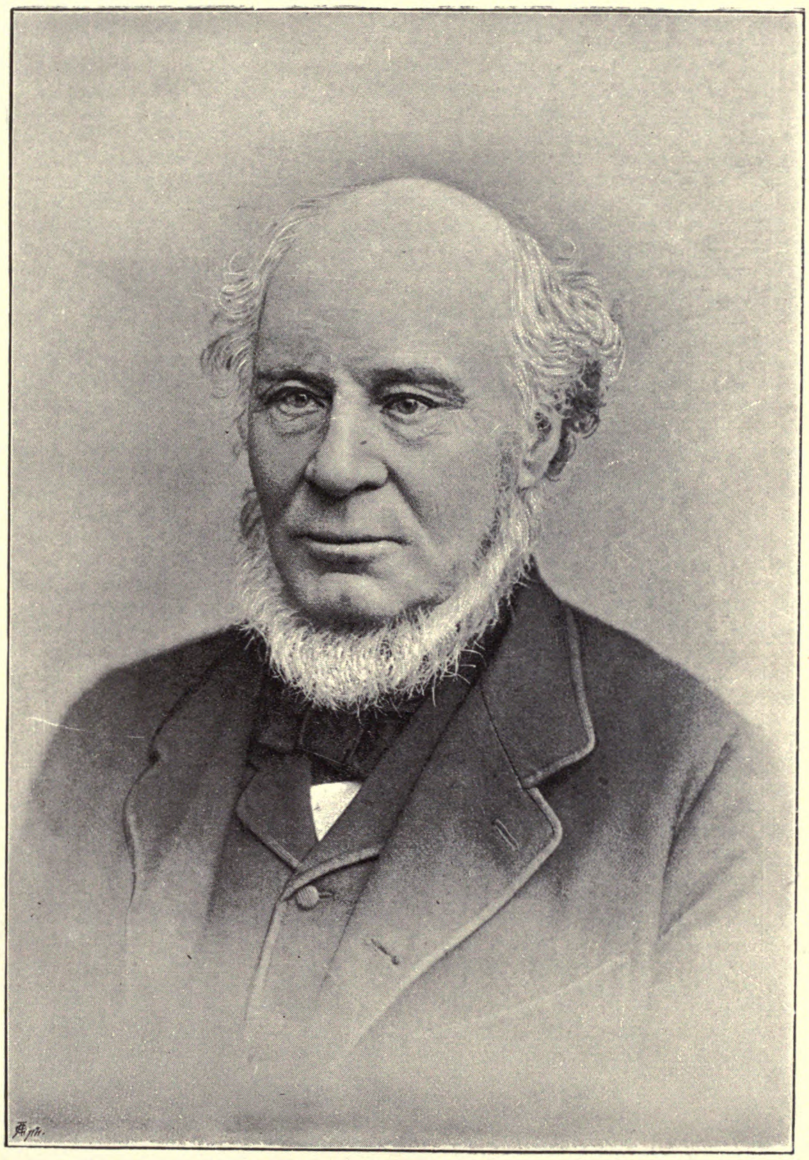
Our work of describing the Forth Bridge would be incomplete without suitable notices of the engineers and contractors upon whom the responsibility of its construction rested. As we have seen, Messrs. Harrison and Barlow took no part in this work ; having finally approved the design, they gave Messrs. Fowler and Baker the task of its execution. It is of these gentlemen, therefore, as well as of Messrs. Tancred, Arrol, Falkiner, and Phillips, and of M. Coiseau, who completed the pneumatic foundation, we shall attempt to give such notices as will convey an idea of their respective careers during the course of which they acquired the experience necessary for carrying out this great work. We have been led to deal with the biography of Sir John Fowler at great length, because his history is the history of the most important period of the profession, and dates back for more than half a century.

Sir John Fowler, K.C.M.G.

The period over which Sir John Fowler's career extends practically coincides with that of the profession of modern engineering. In saying this we do not forget the illustrious men who preceded him, such as Telford, Trevithick, Watt, Smeaton, and Rennie. But these all flourished before the manufacture of iron, and the tools for working it, had so far progressed that it was readily available for every-day use. Many of them executed splendid works in brick and stone, works which will uphold their reputations for centuries, and others of them were capital mechanics. But it was not then practicable to use iron, and particularly wrought iron, for large structural purposes. It is worth while to recall a few instances in exemplification of this fact which is often forgotten. The first flour mill which had iron wheels and shafting was erected by Rennie in 1788. The first iron bridge was designed by French-Italian engineers in 1755, and was attempted to be constructed at Lyons, but the founders proved unable to cast it. In 1777 a cast-iron bridge of 100 ft. span was erected at Coalbrookdale, and this was followed in 1796 by one over the Wear. This latter had been constructed to the directions of the celebrated Tom Paine for a different site. A third bridge was erected by Telford over the Severn about the same date, and he constructed four other cast-iron bridges before the century terminated. Rennie's first iron bridge was opened in 1803 at Boston. It is thus shown that the employment of iron on a large scale during the eighteenth century was practically unknown. In the early part of the nineteenth century, cast-iron was largely used for bridges, for canal aqueducts, for locks, and for dozens of other purposes, only to be supplanted in its turn by wrought iron. When this metal could be obtained cheaply and abundantly, engineering science entered upon a new phase of its existence, and the world commenced to progress at a speed hitherto undreamed of.

It was under conditions such as these that the subject of our sketch entered his professional career. He was born in 1817 at Wadsley Hall, Sheffield, the residence of his father, Mr. John Fowler, and when his general education was completed, the boy, at the age of seventeen, became a pupil of Mr.

PLATE I.



From a photograph by the London Stereoscopic Company.

Yours very truly

John Fowler

J. T. Leather, the well-known hydraulic engineer. Here he had ample facilities for obtaining a thorough training in several branches of his calling, and in all cases his experience was gained in works of very considerable magnitude. Yorkshire enjoys the advantage of possessing a great number of diverse industries, and it was very early in the field as a manufacturing district. From its coal, iron, steel, and woollen trades, in addition to its farming and shipping pursuits, great wealth was rapidly accumulated after the close of the bad times following the Napoleonic wars. The entire world was then the customer of England, and the shrewd people of the Ridings managed to secure a large share of the trade. The county thus was able to find employment for many engineers, and among them Mr. Leather took a leading position. He executed many works for the supply of water, notably those of Sheffield. The Stockton and Darlington line was opened when Mr. Fowler was only eight years of age, and the Liverpool and Manchester Railway when he was but thirteen. He had not completed his pupilage before the rush, which eventuated in the railway mania, commenced.

When Mr. Fowler left Mr. Leather he went straight into the railway world, finding in the office of Mr. J. U. Rastrick a very wide field. He became his chief assistant in the preparation of the drawings and contracts for several railways; among these was the line from London to Brighton. To this latter Mr. Fowler gave great attention, and there is scarcely a bridge or viaduct which was not personally worked out by him. After two years spent in London, he returned to Mr. Leather, and became responsible resident engineer of the Stockton and Hartlepool Railway. After it was completed he remained two years as engineer, general manager, and locomotive superintendent of that and the Clarence Railway. It is no wonder that these engineers of the old school can turn from one subject to another with so much versatility when we consider what an education they had. Instead of having professors to fill them with ready digested knowledge, like the young men of the present day, they were moved from one position of responsibility to another, and their intellects were hardened and invigorated by constant work. Every step they took was an experiment on a working scale, and every fact they learned was imprinted on their memories by the toil and trouble it had cost.

On the termination of this engagement, Mr. Fowler visited, at the invitation of Sir John Macneil, several railways in the neighbourhood of Glasgow, and gave evidence before Parliamentary committees regarding them. He commenced an independent career at the age of twenty-six, and as we have already seen, he started with a broad and solid foundation of experience, suitable for the towering reputation which was to be built upon it. Several important railways were then being promoted from Sheffield, such as the Sheffield and Lincolnshire, the Great Grimsby, the New Holland, the East Lincolnshire, and others, and of these Mr. Fowler became the chief engineer, conducting them through Parliament and carrying them out. It was in the year 1843 that this work was commenced, and before it was completed the railway mania attained its full proportions. The history of that movement has often been written; how fortunes were made and ruined in a day; how men lost their reason in a moment both from good and evil tidings, and how the capital subscribed during those years, often for the wildest undertakings, almost rivalled the days of the South Sea Bubble. We have no intention of redrawing the picture, but the following incident will show at what high pressure engineers were expected to work in those days. One night when Mr. Fowler was asleep in his father's house, a carriage and four drove up to the door, and the household was aroused by loud knocking. On descending Mr. Fowler found that a prominent promoter of railways had called with the purpose of inducing him to undertake the engineering of a new railway from Leeds to Glasgow, and that as an earnest he had brought an order for 20,000*l.*, as a preliminary payment on account of the survey expenses. It then only wanted a very few weeks (quite inadequate for the purpose) before the day of depositing the plans. Mr. Fowler had the prudence to decline the offer, and the carriage of the disappointed promoter went thundering away, the occupant little dreaming how many years would elapse before his plan would be carried out.

It was only men of iron constitution that came unscathed through those times, and many an engineer who would have risen to eminence, had he been able to husband his strength, threw away his life in furthering the schemes of the promoters. When the autumn approached, and the fatal thirtieth of November hove in sight, surveys and drawings had to be made at the greatest possible speed. The hours of the night were annexed—sometimes all of them—to supplement those of the day, while meals had to be taken when they could, or not at all. The deposit of the plans brought rest to the rank and file, but the chief responsible engineer had then to enter upon the still more trying work of preparing for, and attending, Parliamentary committees. Often he had to appear before three or more committees in one day, pitting his wits against those of half a dozen counsel, backed by eminent opposing engineers. The engineer could not imitate the members of the bar, and choose in what cases he would appear and which he would neglect, taking his fees for all. Indeed, it is said that Charles Austin, the leader of the bar in the committees of the House of Commons, had once been engaged to appear before twenty-two committees in one day, and as it was impossible for him to attend to them all, he showed his impartiality by reading his newspaper and attending to none. The progress of committee work was watched with keenest interest by men who did not know an embankment from a cutting, but who took advantage of every turn of the fight to manipulate the share market. They listened to the evidence of the engineer and sold and bought accordingly. If he tripped in his advocacy of a measure, or was foiled in his attack on a hostile scheme, they hurried to anticipate the effect on the money market. Mr. Fowler once met an acquaintance rushing along the corridor of the House in the wildest excitement, and when he stopped him to learn the cause, the man exclaimed, "Don't detain me! Robert Stephenson has broken down in his attack, and I am off to buy a thousand Great Northerns." Everybody gambled in shares, and like all gamblers their choice was determined by the merest trifles. If a line were fortunate, promoters would endeavour to appropriate as much of its name as they could for other lines, in the hope that their particular venture would gain by the association. As an instance Mr. Fowler's Great Grimsby Railway was at a premium, and consequently the name of Great Grimsby was brought in quite irrespective of geographical facts. This was done to such an extent that the then chairman of committee (Lord Devon) exclaimed "What! Great Grimsby again! Go it, Great Grimsby!"

Mr. Fowler had now attained a position which necessitated his permanent residence in the metropolis, and work of all kinds flowed in to him. It is quite beyond the limits of our space to notice, much less to describe, one-half of the matters about which he was consulted or the works he carried out. Amongst them we may mention the following: The Oxford, Worcester, and the Wolverhampton Railways; the Severn Valley Railway; the London, Tilbury, and Southend Railway (in conjunction with Mr. Bidder); the Liverpool Central Station, the Northern and Western Railway of Ireland, the railways of New South Wales and India, the Sheffield and Glasgow Water Works, the Metropolitan Inner Circle Railway, the St. John's Wood Railway, the Hammersmith Railway, the Highgate and Midland Railway, the Victoria Bridge and Pimlico Railway, the Glasgow Union and City Railway, and St. Enoch's Station, the Millwall Docks, the Channel Ferry, and many others.

Mr. Fowler's reputation with the general public of this generation rests to a great degree on his construction of the Metropolitan Railways. These were so far out of the common that every Londoner, and a great many people out of London, took the greatest interest in them. The most extravagant anticipations were indulged in as to the relief they would afford to the streets if they were ever completed. But the difficulties were so enormous that many, if not most, people imagined that they could not be overcome. The directors were constantly being told that they had embarked their own money and that of the shareholders in an impossible enterprise. Engineers of eminence assured them that they could never make the railway, that if they made it they could not work it, and if they worked it nobody would travel by it. Such a catalogue of impossibilities was enough to appal any man, and often faith in the enterprise fell to a low ebb. At such times they would say to Mr. Fowler, "We depend upon you, and as long as you tell us you have confidence we shall go on." It was an awful load to put on the shoulders of a man who had already sufficient to attend to in combating the physical difficulties of the affair. The troubles with vestries and their engineers and officials, with owners of property and their agents, were for many years during the construction of the first section of the Metropolitan Railway tedious and wearying to the last degree. All these were finally overcome, and the line was opened. So far from there being a difficulty in inducing people to travel by it, the traffic astonished the most experienced railway experts. The general public did not take the view laughingly expressed by Lord Palmerston when asked by Mr. Fowler to perform the opening ceremony, "I intend to keep above ground as long as I can." Of course they grumbled at the ventilation, or rather the want of it, and reproached the engineers for not improving it. Originally, when a junction with other railways was not intended, a special hot-water engine without a live fire, and therefore not passing the products of combustion into the air of the tunnel, was proposed. Experiments were made with an engine so constructed, but before it was perfected it was decided to make a junction with the Great Western Railway, and, therefore, locomotives of ordinary construction had to be admitted on the system.

It was in 1853 that the first Act was obtained for a line $2\frac{1}{4}$ miles in length from Edgware-road to Battle Bridge, King's Cross. Plans for extensions westward to Paddington, and eastward to the City, were at once prepared, and the financial support of the Great Western Railway was secured. After a severe fight, the Act for the extended railway was obtained, the plans providing for tunnels and stations large enough to accommodate the broad gauge Great Western trains, as well as the narrow gauge local trains which it was designed to run. There was, however, a difficulty in raising the capital, and it was not till the spring of 1860 that the contract was made, and the works commenced. In 1861 powers were obtained for extending the Metropolitan Railway to Moorgate-street; and in 1864, for constructing the eastern and western extensions to Tower Hill and Brompton respectively. In 1863 a Lords' Committee decided that it would be desirable to complete an inner circuit of railway that should abut upon, if it did not actually join, nearly all the principal termini in the metropolis, commencing with the extension in an easterly and southerly direction of the Metropolitan Railway, from Finsbury Circus at the one end, and in a westerly and southerly direction from Paddington at the other, and connecting the extremities of those lines by a line on the north side of the Thames. The inner circle was the direct outcome of this recommendation.

The construction of the so-called Underground Railway was the means of solving a great many problems which at the time presented much difficulty. Questions which are now fully understood, and which would be undertaken by contractors as a mere matter of course, then were of very grave importance, and had not only to be exhaustively discussed, but to be attacked with the greatest caution. It was not then known what precautions were necessary to insure the safety of valuable buildings near to the excavations; how to timber cuttings securely and keep them clear of water without drawing the sand from under the foundations of adjoining houses; how to undermine walls, and, if necessary, to carry the railway under houses and within a few inches of the kitchen floors without pulling anything down; how to drive tunnels; to divert sewers over and under the railway, to keep up the numerous gas and water mains, and to maintain the road traffic when the railway was being carried on underneath; and finally, how to construct the covered way so that buildings of any height and weight might be erected over the railway without risk of subsequent injury from settlement or vibration. All these points Mr. Benjamin Baker declared, in a paper read some five years ago before the Institution of Civil Engineers, received much anxious discussion and criticism before they were decided upon. Such questions as the admissible stress on brick arches loaded on one haunch only, the extent to which expansion and contraction of iron girders would affect buildings carried by them, the ability of made ground to resist the lateral thrust of arches, and a multitude of similar problems, had to be dealt with tentatively at first, and with increased boldness as experience was gained. As an instance of the confidence which experience gives we may cite the following: doubts

entertained by the engineers as to the behaviour of a compound brick and iron structure led to a timber front being put to the Edgware-road Station, where it rested on a 49-ft. span girder; yet in 1865, when the extension to Moorgate was executed, no hesitation was felt in trusting an elaborate brick and ashlar face wall, weighing 1300 tons, to a continuous girder 135 ft. in length.

It would be tedious and unprofitable to attempt to give a detailed account of the construction of the Inner Circle line, since the lessons taught by it have long ago been incorporated into the routine of engineering practice. It will ever remain a monument to the skill of the engineers concerned in its construction. Of these Mr. Fowler is responsible for the greater part, as shown by the annexed Table, which gives the lengths and percentages due to each.

Inner Circle Railway.

	Length Executed. miles	ch.	Percentages.
Mr. John Fowler, engineer	11	20	86
Mr. Edward Wilson, ,,	0	27	2½
Mr. Francis Brady, ,,	0	28	2½
Mr. Joseph Tomlinson, Jun.	0	35	3½
Messrs. Hawkshaw and Barry	0	58	5½
	13	8	100

The main lines of the Metropolitan and Metropolitan District Railways being complete, Mr. Fowler carried out the lines in connection with them, including the St. John's Wood Railway, the Hammersmith line, the West Brompton line, and others. His original plan, brought before the Parliamentary Committee, included an outer circle as well as an inner circle. Unfortunately, the Committee was induced to reject the outer circle on the faith of certain promises made by another line. These promises have not been practically fulfilled, and the immense advantage of being able to conduct all through passenger, goods and mineral traffic by a perfect and comprehensive scheme around London was lost for ever.

Although somewhat out of chronological order, we may here refer to another underground railway, of which Mr. J. H. Greathead is the engineer. This railway—the City and Southwark Subway—is not opened at the time of writing, but it is rapidly approaching completion, and great hopes are entertained that it will be the pioneer of a new system of railways which will prove as great a convenience as those already in existence in the metropolis. The ventilation difficulty is avoided entirely by the device of using electric power for the propulsion of trains, while the expensive work of diverting sewers and pipes, underpinning buildings, disappropriating tenants, and buying property, is evaded by keeping the tunnels at a very low level. As the line follows, for the most part, the streets, there is little to pay for land, and the chief expense is that of construction. A Bill now before Parliament contemplates the creation of a second railway of this kind from Bayswater to King William-street, E.C., Sir John Fowler, Mr. B. Baker, and Mr. J. H. Greathead being the engineers. If it is made it will prove the greatest advantage to Londoners.

Mr. Fowler was elected President of the Institution of Civil Engineers for the year 1866, and took the chair for the first time in that capacity on January 9. His presidential address was devoted to the subject of the education of an engineer, and was so important and valuable that it has been reprinted and distributed extensively, notably by the Government of India to the engineers in its employment. He began by calling attention to the fact that the exclusive position hitherto held by the English engineers was not likely to continue, since both in France and Germany great efforts were being made to educate young men both theoretically and practically for this profession. Hence, although this was greatly to the advantage of engineering science, it behoved the Institution to see that the distinguished and leading position which had been so well maintained by their great predecessors, should not be lowered by those who came after them. After a short enumeration of the nature of the works and duties which fell to the lot of a civil engineer, he proceeded to enforce the necessity of a full comprehension of the nature and qualites of materials, and the proper adaptation of the design to the materials in which it was to be carried out. He asserted his conviction that it was most important that the early preparation and subsequent study of an engineer should be as extensive as possible, and should embrace every branch of professional practice. The sound knowledge and experience thus acquired would add greatly to his efficiency and value in any special branch. For the railway engineer there was required a thorough knowledge of surveying and earthworks, the capacity to design bridges, earthworks, and tunnels, and a knowledge of the effect of floods and drainage. To this should be added some knowledge of architecture, and a taste for appropriate decoration. The dock and harbour engineer required, he said, much of the general knowledge of the railway engineer, with a vast amount of special knowledge. This included the laws which govern the tide, the set and speed of currents, their scour and silting; also questions relating to the trade to be accommodated, and the methods of dealing with the goods. He would also be required to be cognisant of such matters as harbours of refuge, piers, landing stages, lighthouses, forts, and hydraulic appliances. The water works engineer, in addition to his general qualifications, had to be familiar with the means of collecting information about rainfall, the method of gauging streams, the excavation of reservoirs, conduits, weirs, tunnels, and aqueducts. He must also be competent to superintend and design sewerage works. The mechanical engineer, the speaker continued, dealt with the most varied and numerous subjects of all the branches of engineering. He must understand the laws of motion, of heat, of liquids, and gases; he must be familiar with the strength of materials and the friction of surfaces. On railways he was responsible for the machine tools, engines, and locomotives. For docks he had to design the machinery for working the gates, the sluices, and the cranes. For water works he produced the pumping engines, sluices, valves, stop-cocks, &c. And so on through the entire series of works in which mechanism is employed. The mining engineer needed, in addition to a knowledge of railway and mechanical engineering, the information requisite for sinking shafts, draining workings, excavating and raising minerals, and preparing them for market.

Mr. Fowler then turned to the preparation required by a civil engineer to enable him to perform his work efficiently. This he classed under four heads: (1) General instruction, or a liberal education; (2) special education as a preparation for technical knowledge; (3) technical knowledge; (4) preparation for conducting practical works. He supposed a boy to start at fourteen years of age with a strong constitution, considerable energy and perseverance, and a fair education, together with a mechanical bias. The period from fourteen to eighteen should be devoted, he said, to a special education, including mathematics, natural philosophy, surveying, drawing, chemistry, mineralogy, geology, strength of materials, mechanical motions, and the principles of hydraulics. To these must be added considerable progress in French and German, even at the sacrifice of classical studies and pure mathematics. At the age of eighteen, assuming the boy to have fair abilities and more than average perseverance, three courses were open. He might be placed with a civil engineer for four or five years' pupilage, or in a mechanical workshop, or he might be sent to one of the universities. The choice would depend on the taste of the boy, the means of his parents, and other circumstances. If he followed either of the first two courses it would be necessary for him to continue his studies in mathematics, science, and foreign languages at the same time. If the latter course were adopted, the drudgery of learning to survey, to draw, and the like, must be passed through first. With a clever hard-working boy the most advantageous course might be to send him, from seventeen to eighteen, into a good workshop, then for three years for a university course, and finally into an engineer's office for his pupilage. This, of course, would require a boy of special ability and determination to render it a successful course. The office chosen for the pupilage to be passed in ought to be well organised and not too large; the engineer should be a comparatively young and rising man, and be accustomed to take pupils, who should be few in number, and bear some proportion to the number and extent of the works in usual course of construction under the engineer's direction. Here the pupil ceased to be a boy, and his future success or failure could no longer be directed by others, but depended upon his own abilities and industry.

Mr. Fowler also laid stress on the fact that the whole duties of the engineer were not comprised in the mere accomplishing of the objects entertained by his employers. It was his duty, he held, to advise those who consulted him whether the undertaking was one that would repay the expenditure which must be made upon it. The engineer was not merely a man of technical skill engaged to bridge the difficulties of capitalists, as a servant carries out the orders of his master; on the contrary, he was a member of an honourable and noble profession which could not lend itself to enterprises which did not give fair promise of being beneficial to the world, and to the advancement of civilisation.

In 1870 Mr. Fowler took part in a commission sent to Norway to examine the railways there. As is well known Norway has built a great length of railway which was constructed at a very small cost and is worked very cheaply. Now, at the date mentioned the Indian government were undecided whether to adhere to the broad gauge of 5 ft. 6 in., which had been adopted for the trunk lines, or to introduce a narrower gauge for the less important railways. A commission composed of General Strachey, Colonel Dickens, Mr. Rendel (now Sir A. Meadows Rendel), and Mr. Fowler, was, therefore, sent to Norway, for the purpose of acquiring information as to what gauge should be adopted in India, assuming that it was decided that a narrow gauge should in certain cases be laid down. The commission was received and accompanied by Mr. Carl Pihil, the experienced engineer of the Government, who had carried out all the railways in Norway. They travelled over the Dovre Fjld by carriole, passing over the ground on which a railway has since been constructed, and were thus able to see the nature of the works which would have to be carried out. The Norwegian lines are 3 ft. 6 in. gauge, and the rails and engines are both very light, the speed being usually quite slow. Mr. Fowler considered this gauge narrow enough, and the engines too light for economy. His colleagues, however, took a different view, and recommended 2 ft. 9 in. as the proper gauge for India.

Two reports, therefore, were made, one by Mr. Fowler recommending 3 ft. 6 in. gauge, and one by the other members of the commission, recommending 2 ft. 9 in. The final decision of Government was between the two, but much nearer Mr. Fowler's opinion, viz.—a metre, or 3 ft. 3½ in.

It was understood that the question referred to the Commissioners was not whether narrow-gauge railways should be adopted in India or not, but, supposing a narrow gauge to be adopted, what gauge should it be. Mr. Fowler, from his long experience of the evil on the Great Western Railway, had very strong objections to breaks of gauge except when unavoidable. He would never permit an exceptional gauge in a link, or a possible link line, nor for short branches where exceptional plant would neutralise all saving. He considered that an exceptional gauge should be confined to a district of country where break of gauge is unimportant by reason of non-interchange of traffic, and even then he preferred to adopt a light railway on the standard gauge, except under very peculiar circumstances, which must be very rare indeed, when the narrow gauge would have some special advantages.

Last winter (1888-89) Sir John Fowler had the opportunity of verifying by actual inspection on the spot, the opinion he had formed as to the railway policy of India, and it is well known that he has expressed himself as having had his former conclusions strongly confirmed by his Indian visit.

Sir John visited Darjeeling to see the working of the 2 ft. 6 in. gauge mountain railway, ascending 8000 ft. by gradients of 1 in 27. This curious little railway has been laid on the fine road made to Darjeeling, and, being saved all expenses except that of permanent way, it is not surprising that a good dividend is earned, notwithstanding the fact that the engines can only draw less than twice their own weight up the incline. In this case the gauge and everything else are suited to the traffic, but unless the same circumstances were found the system could not be applied elsewhere with advantage.

Sir John was naturally much consulted, both professionally and otherwise, in India by the authorities on the subject of railways, docks, and water works, and was received everywhere with great distinction. His general impressions of India and its resources were of the most favourable character.

One of the most interesting chapters in Mr. Fowler's career is that connected with Egypt. He went there, in the first instance, in search of health; and the connection thus accidentally formed lasted as long as Ismail Pacha remained in power. As is well known, that enterprising Sovereign threw himself heart and soul into the material improvement of the country. He had unlimited credit in the money markets of western Europe, and he aimed at restoring Egypt to its ancient position as one of the chief producing countries of the world. He brought about a wide extension of the irrigating system of the Delta, in order that crops might follow each other independently of the season of the year; he introduced sugar plantations and factories in Upper Egypt on a most extensive scale; he built several railways, and projected one southwards to Khartoum, which, if completed, would have been the key to Central Africa. He entered upon every scheme with the greatest ardour, and no sooner were the plans completed than he urged the giving out of the contracts and the commencement of the work. In Mr. Fowler the Khedive found the very man he wanted—one whose ability was only equalled by his rectitude. National prosperity, however, is not to be founded by railways, docks and canals alone. Its basis lies in good government and the just administration of wise laws; but it is not our business to go into the politics of Egypt further than to explain the condition of affairs when Mr. Fowler came in contact with them.

He landed in Egypt at the close of 1868. At this time the Suez Canal was within a year of its completion, and it was natural that Mr. Fowler should hurry to see it, even before fulfilling the avowed object of his visit of exploring the antiquities of the country. The trip was made under very favourable circumstances, the party including M. de Lesseps, M. Voisin, the Duke of Sutherland, Sir Richard Owen, General Marshall, the Marquis of Stafford, Mr. W. H. Russell, and others. The works from Ismailia to Port Said, and the harbour works at Port Said, were well advanced, but between Ismailia and Suez nearly one-third, or twenty-five million cubic yards of excavation, remained to be executed. The survey occupied three days, and included the whole length of the canal, everything being explained by M. de Lesseps with the greatest kindness, and the various points being discussed without reserve. At the request of the editor of the *Times* Mr. Fowler addressed a long letter to that journal giving a full account of the state of the works and criticising the prospects of the company. This letter appeared on February 18, 1869, and was made the text of a leading article which pronounced it to be a fair and final summary of the subject by an English engineer of the highest eminence and repute.

In the spring of 1869 the Prince and Princess of Wales visited Egypt. When about to make the journey up the Nile the Prince invited Mr. Fowler and Professor Owen to join the party, which was embarked on five steamers and dahabeahs. Nothing could be pleasanter than to make the excursion under such conditions, as every arrangement was made for the Royal party to see the objects of interest in the country, both ancient and modern. Of course Mr. Fowler had to pay the usual penalty of fame, and to be prepared to suggest the probable methods employed by the Egyptians in raising large stones for the pyramids and temples, and in cutting and polishing the greenstone and diorite statues. At Thebes his engineering resources were severely tried by the Prince's cross-examination as to the manner in which the colossal statue of Rameses II., weighing 888 tons, was brought from the quarry near Assouan to its present position at Memnonium on the plain of Thebes. The excursion proved to be most enjoyable.

Before Mr. Fowler returned home he had several interviews with the Khedive, explaining to him his views concerning the Suez Canal, the irrigation schemes, and many other matters in which Ismail Pacha was interested. The outcome of this was that he accepted the position of consulting engineer to the Khedive and the Egyptian Government, a post which he held for eight years—that is, until the abdication of that ruler. The office involved yearly journeys to Egypt, the first being in the latter part of 1871, and required Mr. Fowler to personally investigate all the great undertakings then in hand. The most important matter presented to him for solution was the projected Soudan Railway. It is needless to say that, although commenced, and 150 miles constructed, it was never carried out, or recent Egyptian history would have been greatly changed, while thousands of British soldiers and millions of money would have been saved.

Mr. Fowler, before deciding between the two possible routes by the Nile Valley and by Souakim-Berber, had long interviews with General Gordon, and also with the governors and other persons acquainted with the country to be traversed. The Nile Valley was ultimately chosen, and the decision ratified by the Khedive and his ministers. The surveys were commenced at once, and when completed the Khedive, with characteristic promptitude, instructed Mr. Fowler to obtain a contract for the work. This was accordingly done, and on February 11, 1875, the works were commenced at Wady Halfa with great ceremony in the presence of Mr. Fowler, the governor of the province, the Cadi, and other notables, bullocks being slaughtered as part of the religious observances. The abandonment of the railway, and all the disasters which followed it were keenly felt by Mr. Fowler, who fully believed that had Khartoum been thus connected with Cairo the turbulent native tribes could have been overawed, and a great economy would have been effected in the long run. Unfortunately it is not given to man to read the future, and when matters went wrong in Egypt the expense of the railway seemed too great for the resources of the country

Although this railway was not completed, and has passed for the moment out of public notice, yet it is a matter of certainty that sooner or later it will be constructed. The eyes of nearly all European nations are concentrated on Africa, and many are striving to secure a firmer foothold on the continent with a view to gaining a share of the future trade which is anticipated. It is certain that when Egypt attains the position which is sure to follow upon a few years of good government, there will be a revival of the old ambitions, and she will turn her attention southward, with that craving for extended sovereignty which is the characteristic of all healthy communities. It will, therefore, be interesting to give a few facts regarding the route, length, and cost of the line which must be made if the flood of Arab invasion is to be permanently dammed. Sir John Fowler always held the opinion that our difficulties in the Soudan came from the undecided attitude we took up. The native tribes could not be neutral; they were obliged to side either with the English or the Mahdi. But the former declared that they had not come to stay; they came to rescue Gordon, and when that was done they would retire, and leave the entire population "to stew in their own juice." This promised to be so highly flavoured with Mahomedan vengeance that the tribes were obliged to cast in their lot with the successor of the Prophet, and fight against the invaders. In the days of Ismail Pacha the Soudan was ruled by the shadow of the authority which existed at Cairo, and Sir John Fowler holds that the same conditions would recur if the railway were completed.

The southern terminus of the line was to be at Metammeh, on the left bank of the Nile, immediately opposite Shendy, 16 deg. 14 min. N. latitude, and 32 deg. 25 min. E. longitude. Shendy is equidistant between Berber and Khartoum, and about 99½ miles from each. It is moreover the converging locality for the camel routes from Khartoum and the White Nile district, from Hamdal, Souakim, and the Red Sea, and from Aboo Kharraz and the Blue Nile. There is good navigation between Berber and Khartoum for ten months in the year, and the obstructions which exist in the low-water channel would not be difficult to remove or lessen. The northern or Egyptian end of the line was fixed at Wady Halfa, at the second cataract. Commencing at the foot of the cataract on the right bank of the river, the line followed the general course of the stream as far as Kohé, this side being chosen to avoid the drift sand from the Nubian desert. At Kohé the line crossed the Nile, and then followed the right bank as far as Dabbe. Here the Nile makes a long detour, and consequently the projected line struck across the Bahiuda desert to its terminus.

The following are the lengths:

	Miles.
Wady Halfa to Kohé	160
Kohé to Ambukol	216
Ambukol to Shendy...	176
	552

The line was one of easy construction, with no works of magnitude except the Nile crossing. When practicable it kept to the villages and cultivated lands on the banks, but sometimes it took an inland course amongst the mountains to avoid expensive works, and sometimes it traversed deserts to cut off bends of the river. The gauge was fixed at 3 ft. 6 in., the same as the Norwegian railways, but with a heavier rail of 50 lb. to the yard; the maximum gradient was 1 in 50, and the minimum radius of curvature 500 ft. The cost, including stations, sidings, quays or landing places, rolling stock, workshops, and all expenses required to complete the line ready for traffic, was estimated at four millions sterling, or 7240*l*. a mile. Of this amount five-eighths would have been spent abroad and three-eighths in Egypt.

It will be noticed that the railway was to start at the second cataract, some 550 miles, as the crow flies, from Cairo. The Nile forms a natural roadway between the two for the entire distance, except for some three miles at Assouan, where the first cataract occurs. To enable steamers and dahabeahs to pass from the lower to the upper level of this cataract, Mr. Fowler conceived the idea of a ship incline, and in company with Sir William (now Lord) Armstrong and Mr. Rendel he went to the site. The necessary surveys, examinations, and estimates were made, and on the return to Cairo Sir W. Armstrong offered to undertake the work, and his proposals were approved. But like many other projects of that time in Egypt, the plan was frustrated by the interference of jealous foreign rivals, and nothing was done.

The plan contemplated the construction on the right bank of the canal of a ship railway 3 kilometres in length, commencing at the bottom of the cataract in the river channel, about 5 kilometres south of Assouan, and terminating at the top of the cataract in the harbour of Shellal. The boats to be transferred were to be floated upon a cradle constructed to run upon the railway, and to be hauled over land by hydraulic engines of 400 horse-power, placed near the centre of the railway. The water to work the engines was to be pumped at a high pressure by a pair of large stream wheels carried upon pontoons, and driven by one of the smaller rapids at the lower end of the cataract. The total length to be traversed over land by the boats was 2950 metres at low Nile, and 2300 metres at high Nile. The estimate of the cost of the incline with machinery, workshops, wharves, and all expenses required to complete it ready for traffic, was 200,000*l*.

One of the first matters claiming Mr. Fowler's attention on undertaking the duties of consulting engineer was the organisation of the existing railways, and to this he devoted much time on his first official visit in 1871. As a preliminary he employed Mr. D. K. Clark to obtain for him full details of the rolling stock and plant. With this information before him, Mr. Fowler was able to advise great changes in the direction of simplicity and economy, most of which were carried out.

The management had previously been of a most unsatisfactory condition. In the year 1869 the expenses per train mile amounted to 7s., of which the locomotive power figured for 3s. 5d. Many other items were needlessly high, and were increased by the practice of keeping duplicate sets of accounts, more or less imperfect, in French and Arabic. Mr. Fowler considered that the expenses could be well cut down to 4s. 6d. per mile, or 36 per cent. of the earnings. This small percentage was due to the very high traffic charges, particularly on the transit railway which conveyed the P. and O. Company's passengers across the isthmus; on this line first-class passengers were charged 4⅜d. per mile, and second-class 2½d.; accelerated goods were charged 4¼d. per ton, and unaccelerated 1d. per ton per mile.

In the same year visits were made to Upper Egypt to examine irrigation works and sluices, and to Suez to determine matters connected with the docks there. M. Duport, on Mr. Fowler's recommendation, was appointed engineer in charge of the new Alexandra Docks, a post which he filled in a highly satisfactory manner till the completion of the works.

In the following year, 1872, the most important matter for consideration was the sugar plantations and factories of the Khedive. Already several millions sterling had been spent upon them with but poor returns, and the time had come when some alteration in working must be decided upon.

To aid him in forming his judgment, Mr. Fowler secured the valuable assistance of Mr. (now Sir Frederick) Bramwell and Dr. Letheby. The result was that reports of the most exhaustive character were presented to the Khedive, and formed a valuable guide for all future operators. The Khedive, however, was too sanguine, and the works were established too rapidly and on too extensive a scale. Possibly the climate was also not quite suitable for sugar cultivation. The broad result was a very serious loss of money to the Government.

During the course of the investigation into the conditions of the sugar estates, several interesting facts, worthy of being placed on permanent record, were demonstrated. It was found that the soil of Egypt, which, of course, is entirely Nile deposit, consists of a large amount of fine sand, mixed with an unctuous clay, in the form of minutely divided double silicates of alumina and iron, together with fine oxides of iron, alumina, potash, alkaline silicates, soluble silica, and a fair proportion of carbonates of lime and magnesia. The soil is in such a minute state of subdivision that it readily yields its most important constituents (silica, phosphoric acid, and potash) to the growing crops. For the cultivation of sugar it is necessary to equalise the excess of potash by the application to the land of more phosphoric acid, and to make up for the deficiency of nitrogen by the addition of ammonia. Analyses were also made on another occasion of the Nile water to determine whether it had, when used for irrigation purposes, any manurial value beyond that due to the suspended mud. The samples were taken about the middle of the months of June, July, August, September, and October. It was found that in each case the water contained a considerable quantity of nitrogenous matter in the form of actual ammonia, as well as ammonia derivable from organic matter. The proportion of actual ammonia was largest in July and smallest in August. The organic ammonia was smallest in the August sample and largest in September. Taking the whole of the ammonia derivable from 100,000 parts of water, the quantity ranged from .0114 parts in the August sample to .0271 in the sample collected in June. These are remarkably large proportions when we consider that the Nile does not receive anything in the nature of sewage or ordinary town drainage, for they are largely in excess of the proportions found in the River Thames at Hampton. The properties of soluble saline matters in the Nile water range from 13.443 parts per 100,000 in October to 18.8 parts in June. The chief ingredients in these saline matters are the carbonates and sulphates of lime and magnesia, but there is also a notable quantity of soda and potassa, as well as a trace of phosphoric acid. The sedimentary matters in the several samples taken amounted to 6.915 parts per 100,000 of water in June, and to 149.157 parts in August; and the proportions of organic matter in the deposit ranged from .829 parts to 18.414 parts. The results show that the water of the Nile is remarkably rich in fertilising matters, for not only does the water contain in solution a notable quantity of ammonia, nitrogenous organic matter, and the soluble silicates of potassa and soda, as well as a trace of phosphoric and nitric acids, but it also contains in suspension a large amount of sedimentary matters which are charged with phosphates and alkaline silicates.

The most important Egyptian question submitted to Mr. Fowler was that of irrigation. Upon this depends to a great extent the fertility of Lower Egypt, for although the annual inundations can be depended upon to give the land one thorough watering, there are many crops that need to be watered several times and at different seasons of the year from that at which the flood comes. Immense irrigation works were constructed by Mehemet Ali, with canals running through the delta and the land on either side of it. For a considerable part of the year these canals served their purpose fairly well, but at the period of low Nile many of them became useless because they were at too high a level. This does not arise from any error of the designers, but from the fact that the barrage, which was built to maintain a minimum depth of water in the river, did not prove capable of resisting the required head Hence it was necessary to allow the river to fall below the proposed level. Under these conditions Mr. Fowler was instructed (1) to prepare alternative plans for placing all the cultivated and cultivable lands of Lower Egypt in a position to be irrigated at any time of the year without pumping; (2) to devise an improved means of introducing flood water several times during high Nile upon any required lands on the left bank of the Nile, and of discharging it at pleasure without interference with other lands; (3) to prepare a scheme for the construction of a ship canal between Alexandria and Cairo. Mr. Fowler proposed as alternative projects under the first head; (1) a high level canal on the right bank of the Nile; (2) a high level canal on the left bank of the canal; (3) the completion of the present barrage or the construction of a new one. None of these proposals were then carried out, but during the past few years, under the superintendence of Colonel Sir Scott Moncrieff, the barrage has been repaired to such an extent that it will hold the water up to 3 metres, instead of 4.5 metres, as contemplated by Mr. Fowler. The methods employed in the repair of the barrage followed the lines laid down by Mr. Fowler, but were on a less extensive scale, as the pressure to be resisted was less, and there was greater difficulty in obtaining money than during Ismail Pacha's time. The deficiency of head is made good by pumping into the higher canals.

The second undertaking required a canal starting very high up the Nile, and following the course of the Bahr Yousuf, but it presented no features of special engineering interest, and was not attempted. The third, the ship canal, was a subject in which Ismail Pacha took the greatest interest. He found that the effect of the Suez Canal was to divert the traffic from the capital, and to take the stream of passengers through the country without adding anything to its wealth or importance. He, therefore, conceived the idea of making Cairo into a seaport, with easy access to the Mediterranean. Mr. Fowler worked out a combined irrigation and ship canal from the Mediterranean to the Red Sea, by way of Cairo. This canal would have been a formidable rival to the Suez Canal, in so much as the dues derivable from the irrigation water would have enabled the tolls on ships to have been reduced to a very low figure. In the negotiations which subsequently took place with the Suez Canal Company, the possibility of the second canal being made, served as a powerful lever in the hands of the English party.

Although so many of Mr. Fowler's Egyptian schemes were not carried out, we must not regard them as wasted effort. For thousands of years Egypt has been the prey of conquerors of many races and creeds. Probably for the first time in her history she is in the hands of a power which has no selfish aims, and thinks solely of the good of the inhabitants. Under such conditions she must prosper, and the time is certain to come when many of the ambitious schemes of her late ruler will become possible of realisation. At that moment the reports and drawings of Mr. Fowler will be turned to as the key of the plans to be adopted.

Space does not permit us to particularise all the great works in Egypt with which Mr. Fowler was concerned, such as the construction of steamers for the Khedive, surveys for a railway to Harrar, and many others. For nine years he made periodical visits to the country, and became greatly interested in its fortunes. The connection was broken, however, when Ismail Pacha was made to abdicate, and a new era of economy was introduced. Egyptian credit was almost exhausted, and what little was left was destroyed by the revolt of Arabi Pacha. A few years later (1885) the Queen, on the recommendation of the Marquis of Salisbury, created Mr. Fowler Knight Commander of the Order of St. Michael and St. George "for important services and guidance to Her Majesty's Government in connection with Egypt."

A curious example of the way that the engineer may be useful in averting political troubles is found in one of the incidents of Mr. Fowler's career. The Italian premier, M. Minghetti, had disagreed with Garibaldi on the question of the rectification of the Tiber. The popular patriot was powerful at the time in Italy, and wielded an influence which the Government did not care to have exercised against themselves. At the same time they did not feel able to accept his views on the particular question before them. Mr. Fowler was at that time at Cairo on one of his Egyptian visits, and it was decided to submit the matter to him. He was accordingly summoned to Rome, and was fortunately able to reconcile the differences of the two parties, to the great relief of the Government.

We now come to the Forth Bridge, the best known of all the works with which Sir John Fowler has been associated, and one which at the present moment is engaging the attention both of the general public and of engineering experts in all parts of the world. Sir John lays no claim to be the sole author of the design which was the joint outcome of four minds, all bent on discovering the best and cheapest means for carrying a railway over the Firth of Forth. Most people will remember that when the Tay Bridge was destroyed, preparations were being made, and were actually commenced, for bridging the Forth. Sir Thomas Bouch had designed a suspension bridge for the purpose, and an Act of Parliament had been obtained authorising its construction. The failure at the Tay at once threw doubts upon the safety of the most ambitious project, and the works were stopped. Subsequent investigation showed that the proposed bridge could not have been a satisfactory one.

A bridge across the Forth offered so much advantage to the railway companies forming the east coast route to Scotland that, after two years, the idea was revived. On February 18, 1881, the four great railway companies concerned, the Great Northern, the North-Eastern, the Midland, and the North British, wrote to their consulting engineers—Mr. T. Harrison, Mr. W. H. Barlow, and Mr. John Fowler, associated with Mr. B. Baker — propounding two questions for their joint opinions. They were asked to consider the feasibility of building a bridge for railway purposes across the Forth, and, assuming the feasibility to be proved, what description of bridge would be most desirable to adopt. The matter involved so large an expenditure and contained so many novel issues that it needed to be approached with the greatest possible care. It was fairly well known how many types of bridge there were to select from for such a site;—these were (1) Mr. Bouch's original design; (2) a stiffened suspension bridge; (3) a second form of stiffened suspension bridge; (4) a cantilever bridge. Calculations of weight and cost were made for each type of bridge and were discussed by Messrs. Harrison, Barlow, Fowler, and Baker, with the general result that the cantilever type was chosen. A report was made to the railway companies on May 4, 1881, embodying the result of the deliberations, and pointing out that the cantilever principle offered a cheaper and better solution of the problem than any other. The report did not enter into the details of construction; indeed it could not be said to give even the broad features, other than those which are involved in the use of the cantilever. These still remained to be elaborated in council, and it was only by united discussion that the original plan developed into the final design. Although the type of the bridge is very ancient there were many features in it which were open to consideration, and to differences of opinion, and at each meeting of the engineers new ideas were propounded, and novel methods of overcoming difficulties were mooted. After most elaborate investigations and calculations the structure gradually, by a process of evolution or development, assumed its present form.

The design being settled and the execution decided upon by the associated railway companies, the carrying out of the work was entrusted to Mr. Fowler, in conjunction with his partner, Mr. Benjamin Baker.

The Parliamentary fight had been exceedingly stubborn, for great interests were at stake. Hitherto the London and North-Western and the Caledonian companies have enjoyed a great advantage in carrying the Scotch traffic to Perth and the Highlands, in consequence of the east coast traffic having to traverse the circuit from Edinburgh *viâ* Larbert and Stirling to Perth. But when the bridge is opened this advantage will disappear. A very strong hybrid semi-public committee was appointed, with Lord Stanley, of Preston, the present Governor of Canada, as the chairman. Engineering evidence was brought forward to condemn the structure, and every possible description of hostile evidence for shipping interests was adduced against it, and made the most of by eminent counsel, who both in speeches and cross-examination strove to the utmost to prejudice the undertaking. But at the close of the case the committee were unanimous in favour of the Bill, only stipulating that the Board of Trade should maintain a general inspection of the works during construction. It was finally arranged at the suggestion of Mr. Fowler that the inspectors should report to Parliament every three months as to the progress of the bridge, and the quality of the materials and workman-

From a photograph by Bassano.

Yours faithy

B. Baker

ship. These reports, made by General Hutchinson and Major Marindin, have appeared regularly in our columns, and all have spoken in the highest praise of the way in which the undertaking was being carried out.

Sir John Fowler and Mr. Baker have kept a personal and continuous control over the entire operation of building the bridge, and have superintended the series of processes, from the rolling of the plates to the closing of the rivets. They have further employed several distinct staffs of assistants for the purposes of (1) surveying and foundation work; (2) for working drawings; (3) for inspecting plates at the mills; (4) for inspecting the rivetting; and (5) for the fitting and erecting. Mr. Alan Stewart was chief of the staff in Westminster, where all the detailed drawings and calculations were made. The resident engineer was Mr. Cooper, who entered Mr. Fowler's office in 1863, and has remained there ever since. Mr. Tuit, Mr. Lilliquist, and Mr. Carey, and other engineers of exceptional ability were also on the engineers' staff. The contractors were selected on account of their previous experience. Mr. Phillips had had great experience in bridge building; Sir Thomas Tancred and Mr. Falkiner in large contracts and the organisation of labour; and Mr. Arrol had shown on previous occasions remarkable ability and resources. In the early days Mr. Phillips took an active part, but in the preparation and erection of the steel Mr. Arrol took the leading position, and he was ably seconded by Mr. Biggart, Mr. Moir, Mr. Westhofen, Mr. Harris, Mr. Scott, Mr. Bakewell, and others.

Having brought this series of sketches of incidents in the career of Sir John Fowler up to the commencement of the Forth Bridge, we do not propose to carry it further. In the columns of this issue will be found full details of the design and construction of that magnificent work. The bridge, however, has not monopolised the whole of Sir John Fowler's time and attention; he has been connected with many other important works in the meantime, besides fulfilling his standing engagements. Sir John became consulting engineer, on the death of Mr. Brunel, to the Great Western Railway, and besides this and many smaller undertakings, he is consulting engineer to the Great Northern, the Brighton, and Highland railways.

Mr. Benjamin Baker.

The career of Sir John Fowler, which we have endeavoured to sketch in the foregoing columns, may be regarded as a contribution to the early history of the profession rather than as a biographical notice. When Mr. Baker began his career, Sir John Fowler had been actively engaged in a variety of important work for more than twenty years. The great pioneers of the profession had, most of them, either passed away, or had retired from active service, their work having been continued by those who had served with them, benefiting by their experience, and enlarging it with their own. Engineering had, in fact, been reduced to a science that replaced the more or less experimental pursuit which had occupied the previous generation, and the foundation had been securely laid for the development which to-day distinguishes the profession throughout the world. But it was not alone the early engineers who bequeathed a rich inheritance of experience to their successors. Industry and applied science in every direction which could be useful to constructive work were progressing steadily and with rapidity. Especially this was the case with the manufacture of iron, which rendered undertakings easy that would have been impossible to the older engineers, who had little at their disposal except timber, stone, and brick. And later, when, in the march of progress, iron had to give way to steel, engineers were enabled to undertake and carry out successfully, undertakings which their immediate predecessors could not seriously consider for want of the proper materials.

In the atmosphere of enthusiasm that naturally surrounds the successful completion of so vast a structure as the Forth Bridge, one is too apt to forget, in presence of the stupendous work, how much is due to the great army of workers who have laboured—blindly in some cases—since the beginning of the century, and to ascribe some of the credit to its creators which is really due to the general advance in mechanical science characteristic of the age. As Lord Brassey said on a recent public occasion, "I like to remember that if my father had not laboured I should not be Lord Brassey." In his many public utterances on the subject of the Forth Bridge Mr. Baker has always brought this fact prominently before his audience. Speaking at Southampton seven years ago, he said: "The merit of the design, if any, will be found, not in the novelty of the principles underlying it, but in the resolute application of well-tested mechanical laws and experimental results to the somewhat difficult problem offered by the construction of so large a bridge across so exposed an estuary as the Firth of Forth." At Montreal, two years later, when the works were in full swing, he said: "If I were to pretend that the designing and building of the Forth Bridge was not a source of present and future anxiety to all concerned, no engineer of experience would believe me. Where no precedent exists the successful engineer is he who makes the fewest mistakes." At Newcastle, last year, when delivering the workmen's lecture of the British Association to an audience of 4000 men, he remarked that the success of the work was due as much to the individual and collective pluck and ingenuity of the workmen as to the scientific labours and organisation of the engineers and contractors; and as President of the Mechanical Science Section of the Association at Aberdeen, he said: "I have no doubt that as able and enterprising engineers existed prior to the age of steam and steel as exist now, and their work was as beneficial to mankind, though different in direction." It is quite clear, therefore, that Mr. Baker does not labour under the common illusion that a very great undertaking must necessarily be the work of very great men; and, indeed, he told the Mechanical Engineers at Edinburgh that he would be sorry not to believe that there were plenty of engineers and contractors in England, Europe, and America capable of building a Forth Bridge, if called upon to do so; and that, in his opinion, if the engineers and contractors of the Forth Bridge deserved the praise which had been so liberally awarded them, it could only be on the grounds that they had done their work as well, probably, as any one else would have done it.

Sir John Fowler's professional training began with level and theodolite in the north of England, and Mr. Baker's with hammer and chisel in one of the oldest ironworks in South Wales. After the usual preliminary training of an engineering student, Mr. Baker was articled to Mr. H. H. Price, civil engineer, in whose workshops and drawing-office he acquired practical experience in foundry, forge, and manufacturing processes, and the designing of machinery and ironwork of all kinds. At the works referred to were made, a hundred years ago, Trevithick's first Cornish pumping engines; and long before the eve of the Liverpool and Manchester Railway, strange locomotives, with spur gearing and racks, and others with double bogies, some of which have been illustrated by us, were turned out of the works, together with marine engines and steamboats of the earliest type. The portfolios of working drawings thus embodied the whole history of the development of the steam engine in its application to railways, navigation, mining, smelting and rolling metals, and to other purposes. After three years practical work at this branch of engineering, Mr. Baker then underwent a further period of training elsewhere in surveying, levelling, and the designing of works in masonry and brickwork. Shortly after his arrival in London, Mr. Baker entered Sir John Fowler's office, and then gradually took a more and more active part in the many important engineering works then being carried out and proposed, including amongst others the Metropolitan Railway, and other railways in and around London.

Mr. Baker was at that time a constant contributor to the columns of Engineering, and his articles on "Long-Span Bridges," first published by us, twenty-three years ago, were soon after republished in America, Germany, Austria, and Holland. From these early days to the present time, Mr. Baker has been associated, in one capacity or another, with important bridges too numerous to mention in different parts of the world; the latest and biggest of which, the Channel Bridge, Mr. Baker, as stated at the Society of Arts, undertook to investigate as an interesting scientific problem, out of consideration to the high position of its promoters and designers, Messrs. Schneider and Hersent, and not as a promoter of the project himself in any sense of the word, but confining himself entirely to the consideration of the question of the best design, and the probable cost of Messrs. Schneider and Hersent's bold project. Whilst on the subject of bridges it may be interesting to recall Mr. Baker's statement at the Institution of Civil Engineers, that it had fallen to his lot to repair and strengthen the three great historical bridges of their first President, Telford; namely, the Menai Suspension Bridge, the Buildwas cast-iron arched bridge, and the Over masonry arch bridge across the Severn near Gloucester, and that he had succeeded in restraining the local authorities from pulling two of them down, or doing anything which would affect the appearance of these works as left by his great predecessor Telford.

Although in connection with the subject of the Forth Bridge it is fit that we should refer at some little length to Mr. Baker's connection with bridge engineering, the Proceedings of the Institution of Civil Engineers, the "Encyclopædia Britannica," and many other publications, and our own columns, bear witness that he is no less interested professionally in tunnelling, ship railways, or other classes of work offering the fascination of novelty and difficulty. Mr. Baker holds an official position under the War Department as a civil member of the Ordnance Committee, to whom all questions affecting the design of guns are referred. He has also advised the Metropolitan Board of Works during the past twelve years, and many other public bodies, on important engineering works of a varied character projected or undertaken by them.

Mr. Baker is a Member of Council of the Institution of Civil Engineers; of the Society of Arts; of the British Association for the Advancement of Science; and also Past-President of the Mechanical Science Section of the latter Association. He is an Honorary Member of the Society of Engineers; of the American Society of Mechanical Engineers, and of other scientific and literary bodies; and a Lieutenant-Colonel in the Engineer and Railway Volunteer Staff Corps.

Sir Thomas Tancred.

Sir Thomas Telby Tancred, the eighth baronet of his line, was brought up in the office of the well-known engineer, the late George Willoughby Hemans. He left England in 1865, shortly after the term of his pupilage had expired, and obtained a position in the Public Works Department of New Zealand. After a time he abandoned the profession in favour of sheep farming, in which pursuit he distinguished himself, becoming a famous breeder, and receiving many medals at different exhibitions. In 1876 Sir Thomas Tancred returned to England, and became associated with Mr. Falkiner as consulting engineer for the New Zealand Government, the business being carried on under the title of Messrs. Hemans, Falkiner, and Tancred, and under that of Falkiner and Tancred, as contractors for public works. The partnership was dissolved in 1886, and afterwards Sir Thomas carried out large contracts in Asia Minor, besides completing the Delagoa Bay railways, a work that was very rapidly executed under his own supervision. He is at present engaged in constructing a railway across the Isthmus of Tehuantepec, over nearly the same route as that located by the late Captain James B. Eads for his proposed ship railway. Sir Thomas Tancred became an associate member of the Institution of Civil Engineers in 1868, and like Mr. Falkiner has practised as an engineer, besides having been a contractor on a large scale for public works.

Mr. William Arrol.

Mr. William Arrol, like many other famous contractors, is essentially a self-made man, who has risen from the humblest position occupied by a worker in iron, to that of one of the principal contractors in the United Kingdom. Mr. Arrol, who was born at Paisley, was apprenticed to a local blacksmith at the age of thirteen; he learned his trade for four years, and it need not be said that he learned it well. By the time he became a journeyman, a financial crisis paralysed Scotland, and work being difficult to obtain, he went to England, where, for a considerable time, he followed his trade, and acquired a varied stock of knowledge that was to serve him well at a later period. Always learning, and always saving money, to aid him in commencing the independent career of which he had already laid down the main outlines, Mr. Arrol—when times grew better—returned to Scotland, and found employment in various capa-

cities, for all of which he was thoroughly fitted, by virtue of his energy, industry, and versatile talent. Whether working as a blacksmith, a fitter, or a boilermaker, his work was well done, and was always characterised by the touch of originality which distinguishes the man born to command from the one made only to obey. To do everything he undertook well, to forsake the grooves prescribed by established handicraft, for new and bolder ways, and never to avoid a menial task that might accompany the undertaking in hand, was characteristic of Mr. Arrol. Speaking recently to some of his friends who presented him with a mark of their esteem, he said: "Whatever I went to I put my whole mind to. Sometimes I was sent to clean the flues instead of repairing the boilers, but I never shirked the duty." It is in this that lies one of the chief causes of his success, "that he never shirked his duty." It was inevitable that Mr. Arrol should rise and rise quickly; before long he changed from the man-of-all-work to the foreman of the bridge and boiler departments, in the works of Messrs. Laidlaw and Sons, of Glasgow and Edinburgh. Here he remained for some years, gaining the experience which was necessary for his coming advancement. Twenty years ago the time arrived when he considered himself justified in making his first and independent venture, and he boldly launched himself as a contractor and repairing engineer, with the munificent capital of 85*l*.—the savings of his life. Success was certain, though Mr. Arrol did not know it, because he had the good fortune to possess the elements that, when combined, command success. It is interesting to know that twenty years ago he purchased his first engine for 18*l*., his first boiler for 25*l*., and the few tools he could afford, and which we may be sure he knew how to select to the best advantage, and how to turn to the best account. How many times during the last few years must Mr. Arrol have recalled this, his first poor but all-important venture, as he walked through the enormous shops and works he laid down to carry out the Forth Bridge contract. For two years after he started in business for himself, Mr. Arrol's life was that which has been led by thousands of other men under similar circumstances, a period of hope and disappointment, of waiting made tolerable only by patience and determination to succeed. In his case, however, success came early, and within three years he had advanced so far in means and reputation, that he was intrusted with the contract for iron bridges on the Glasgow, Hamilton, and Bothwell Railway, one of them being a very large structure spanning the Clyde. Then followed the erection of another important bridge over the Clyde adjoining the Glasgow Central Station of the Caledonian Railway, and it was for this work that Mr. Arrol devised a number of special machines for drilling and rivetting up work, which, with necessary modifications, were so largely used on the Forth Bridge. The Forth Bridge Company in 1873 entered into a contract with Messrs. W. Arrol and Co. for carrying out Sir Thomas Bouch's design, and when the scheme was abandoned, after the failure of the Tay Bridge, the reconstruction of this work came into Mr. Arrol's hands, and was carried out by him between the years 1882 and 1887. In the mean time Sir John Fowler and Mr. Baker had decided that they could safely place the most important part of the work of the Forth Bridge contract in Mr. Arrol's hands, and it is needless to say that Mr. Arrol has justified the confidence which the engineers placed in him.

From a photograph by John Fergus, Largs.

MR. WILLIAM ARROL.

Mr. Travers Falkiner.

Mr. Travers H. Falkiner is a member of a well-known family long since settled in Ireland, of which his brother Richard Falkiner, of Mount Falcon, County Tipperary, is the head; he has been a member of the Institution of Civil Engineers since 1863. Like Sir Thomas Tancred, he was a pupil of the late George Willoughby Hemans, and until the death of that well-known engineer, was closely associated with him in professional work, as assistant, representative, and finally as partner, together with Sir Thomas Tancred, in conjunction with whom he acted as consulting engineer to the New Zealand Government. In 1876 this connection was extended by Mr. Falkiner and Sir Thomas Tancred becoming contractors on a large scale, and together they executed many important works, including railways, harbours, piers, water works, sewage works, and arterial drainage. Previous to his taking up a part of the Forth Bridge contract, he had carried out for Sir John Fowler and Mr. Baker, the Limerick and Kerry Railway, the Tralee and Ferrit Railway and harbour, and the Didcot, Newbury, and Southampton Railway, works amounting to 1,500,000*l*. Amongst other undertakings completed by him in Ireland, are the Dungarvon and Lismore Railway; the Killorglin Railway and water works for Waterford, Wexford; and the Rathmines and Rathgon townships, Dublin. Although in important practice as a contractor, Mr. Falkiner has never abandoned his connection as a civil engineer, and has been associated in that capacity with several works of considerable importance.

Mr. Joseph Phillips.

The fourth member of the firm of contractors for the Forth Bridge, Mr. Joseph Phillips, commenced his professional career in 1844, as a pupil to Messrs. Grissell, of London, and after serving his time he entered the service of Messrs. Fox, Henderson and Co., who were then building the Exhibition of 1851. When the firm erected the Crystal Palace at Sydenham, Mr. Phillips acted as one of their outdoor superintendents, and he afterwards was in charge of the construction and erection of Newark Dyke Bridge, on the Great Northern Railway, the largest ever constructed on the Warren truss principle. His next work was the Birmingham Railway Station roof, which is of 212-ft. span, and at that time was by far the largest roof in existence. Since then Mr. Phillips has frequently been consulted by engineers on the subject of large-span roofs, and has carried many into execution. While still in the employment of Messrs. Fox and Henderson he paid much attention to the system of sinking caissons by compressed air, invented by Mr. Hughes, and first adopted in constructing the foundations of the Rochester Bridge by Messrs. Fox, Henderson, and Co.

Mr. Phillips joined the firm of Messrs. Cochrane and Co., of Dudley, in 1856, as their manager, and he subsequently undertook for them the erection of such well-known structures as Westminster Bridge, and the Charing Cross and Cannon-street railway bridges over the Thames. He was also associated with the same firm in the construction of the bridge across the Mersey at Runcorn. Further recognition of his ability came with the adoption of his patent for wrought-iron caisson cofferdams, put down by open sinking or by compressed air, for the most difficult parts of the Thames Embankment, and, by the Government, at the Spithead forts. Later on he was associated with the late Mr. T. Parry in the contract for the Central Railway Station and line at Liverpool, and the Whitehaven Docks. He afterwards carried out by himself the contracts for the Campos Bridge over the River Para, for the Brazilian Government; the extension of the Derby Water Works (under Mr. Hawkesley), and the Great Western Dock at Plymouth, for the Great Western Railway Company. The foregoing are only some of the works upon which Mr. Phillips has been engaged, but, of course, he has besides undertaken many others, for which much skill and ability were necessary

Mr. Phillips' career has been all the more remarkable because he was removed from active life for a long while by a very serious illness, at a time when he was busily engaged upon important matters, and which, after his recovery, left him in a much less advantageous position for progress than he had formerly occupied. Since the starting

of the Forth Bridge seven years ago he has resided on the spot. Mr. Phillips was specially interested in the sinking of the deep foundations of the main piers, and in the execution of which the contractort co-operated with the eminent French conractors M. Coiseau. The difficulties of that part of the undertaking will be realised by what we have already said. Since the foundations were completed, Mr. Phillips has been actively engaged with Mr. Arrol in superintending the erection of the superstructure.

Monsieur L. Coiseau.

It would be, of course, too much o say that the foundations for the piers of the Forth Bridge could not have been so successfully carried out by English workmen and the firm of contractors who executed the remainder of the work; but it is certain that it was a wise decision to entrust this part of the undertaking to some one who had achieved a high reputation in the specially difficult work of sinking large foundations to a considerable depth, by means of compressed air. On the Continent works of this kind had been carried out on a much larger scale, and under greater difficulties than in this country, and no firm in the world has earned so high a reputation in this field as MM. Hersent and Couvreux. At the time—about 1880—when these contractors were carrying out the Antwerp Harbour works, at a cost of more than a million and a half sterling, their engineer-in-chief, M. L. Coiseau, had the responsibility of the foundations, a work similar in many respects to those of the Forth Bridge. Before this M. Coiseau had been engaged on heavy contracts upon the Suez Canal and the regulation of the Danube at Vienna. For a time he was a partner of Sir Thomas Tancred, and so became familiar with English methods of carrying out work, while at the same time he grew to be favourably and widely known by English engineers. It was during this period that he constructed a railway in Asia Minor. At the present time M. Coiseau is engaged in completing a large contract for the improvement in the port of Bilbao, on extensive railway undertakings in South America, and on other important works. There is no occasion for us to enlarge here on the manner in which he carried out the sub-contract for the sinking of the Forth Bridge caissons, as the details have been given on a previous page, but we may add that many important appliances used for pneumatic foundations have been designed by M. Coiseau.

APPENDIX.

INSPECTION AND TESTING OF THE FORTH BRIDGE BY THE BOARD OF TRADE.

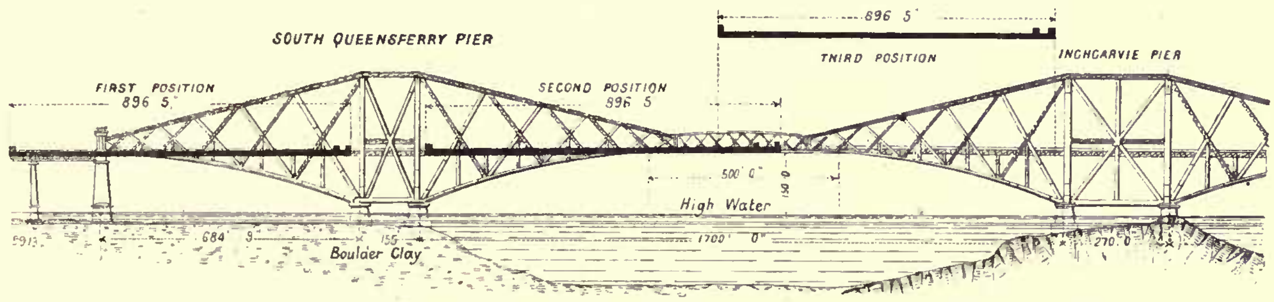


Fig. 157. Diagram showing positions of test loads.

The official inspection and testing by the Board of Trade Inspectors took place on Tuesday, the 18th February, and the two following days. The inspectors were Major-General Hutchinson, R.E., Major Marindin, R.E., and Major Darwin, R.E., and they were assisted by Mr. W. N. Bakewell and his assistants, of the Forth Bridge Surveying Department.

The conditions, as regards the structure, were the same as on the occasion of the preliminary trials excepting the following:—Ballast, consisting of coarse screened gravel to the extent of about 600 tons, had been distributed over the structure, being laid over the buckle-plates in the 6-ft. way, and between the troughs of the two lines; on the other hand a considerable amount of staging suspended from the cantilevers and central girders had been removed. The dead-weight in the end boxes of the two fixed cantilevers had also been increased to 1000 tons in each case.

The trains used on this occasion consisted of:

2 Locomotives and tenders in front ...	146 tons.
44 Wagons (loaded with pig iron) at 15 tons 10 cwt.	682 ,,
1 Locomotive and tender in rear	73 ,,
Total for each train...	901 ,,
Or for both trains...	1802 ,,

The length of each train was:

3 Engines ...	144 ft.
44 Wagons ...	752 ft. 5 in.
Total ...	896 ft. 5 in.—close buffered.

The load was thus somewhat more concentrated than on the first occasion.

Along the footpaths on both sides of the internal viaduct stations had been prepared by driving in copper tacks upon which the levelling staffs were placed. There was a station at the centre of each tower, at each of the vertical columns, and at the ends of each bay in the cantilevers, also at each end and at the centre of the central connecting girders. All stations had been levelled several times over, and carefully checked and plotted. On the morning of the inspection, and previous to any train being allowed on the structure, the whole of the stations were gone over again, both by the Forth Bridge surveyors and, subsequently, by the officers of the Board of Trade—Major-General Hutchinson taking one side and Major Marindin the other. The stations in the cantilever end piers and at the vertical columns were taken as fixed points, and all other levels were referred to these as benchmarks.

First Position of Trains.—The trains were now moved side by side over the south approach viaduct and along the Queensferry south cantilever until the front engines were close to the south vertical columns. Levels were now taken on both sides at every station, but only maxima are here recorded—the intermediate deflections were throughout in proportion.

Deflection at ends of Bays 2 and 3 on east side = $1\frac{1}{4}$ in.
,, ,, ,, west side = 1 in.

Second Position of Trains.—The trains were next moved forward on to the Queensferry north cantilever, the front engines being 6 bays into the south central girder—the rear engine being about 40 ft. clear of the Queensferry north vertical columns. The results were as follows:

Deflection at end posts of Queensferry north cantilever, on east side ... ... = $7\frac{5}{8}$ in.
Ditto, ditto, on west side ... ... = $7\frac{5}{8}$,,
Deflection at end post of Inchgarvie south cantilever, on east side ... ... = $2\frac{1}{8}$,,
Ditto, ditto, on west side ... ... = $2\frac{1}{8}$,,
Upward deflection in Queensferry south cantilever at end of bay 3, on east side ... = $1\frac{1}{4}$,,
Ditto, ditto, on west side ... ... = $1\frac{1}{2}$,,

Third Position of Trains.—The trains were then moved on to the Inchgarvie south cantilever, the front engines being about 40 ft. short of Inchgarvie south vertical columns, the rear engine 6 bays in south central girder. The results were:

Deflection at end post of Inchgarvie south cantilever, on east side ... . = $7\frac{1}{8}$ in.
Ditto, ditto, on west side ... ... = $7\frac{1}{8}$,,
Deflection at end post of Queensferry north cantilever ... ... not observed
Upward deflection at end post of Inchgarvie north cantilever, on east side ... ... = $3\frac{7}{8}$ in.
Ditto, ditto, on west side ... ... = $3\frac{7}{8}$,,

Fourth Position of Trains.—The trains were next moved into the Inchgarvie north cantilever, the front engines 6 bays into the north central girder—the rear engines 40 ft. outside Inchgarvie north vertical columns. The results were:

Deflection at end post of Inchgarvie north cantilever, at east side ... ... = $7\frac{1}{8}$ in.
Ditto, ditto, on west side ... ... = $7\frac{1}{8}$,,
Deflection at end post of Fife south cantilever, on east side ... ... = 2 ,,
Ditto, ditto, on west side ... ... = 2 ,,
Upward deflection at end post of Inchgarvie south cantilever ... ... = $3\frac{5}{8}$,,
Ditto, ditto, on west side ... ... = $3\frac{3}{4}$,,

This concluded Tuesday's work.

Wednesday, 19th February, 1890.—The position of the locomotive engines were reversed this day—one in front, two in rear. The weights and lengths of trains remained the same.

Fifth Position of Trains.—The trains were first moved into the Fife south cantilever—the front engine about 40 ft. short of the Fife south vertical columns—the rear engines 6 bays within north central girder. The results were:

Deflection at end post of Fife south cantilever, on east side ... ... = $7\frac{1}{2}$ in.
Ditto, ditto, on west side ... ... = $7\frac{1}{2}$,,
Deflection at end post of Inchgarvie north cantilever, on east side ... ... = 2 ,,
Ditto, ditto, on west side ... ... = $2\frac{1}{4}$,,

Upward deflection in Fife north cantilever—

End of Bay 2, on east side ... ... = $1\frac{1}{2}$,,
,, ,, on west side ... ... = $1\frac{1}{2}$,,
End of Bay 3, on east side ... ... = $1\frac{3}{4}$,,
,, ,, on west side ... ... = $1\frac{1}{2}$,,

Sixth Position of Trains.—The trains were then moved into the Fife north cantilever—the front engire

outside the north cantilever end pier upon the viaduct—the rear engine 40 ft. short of the Fife north vertical columns. The results were as follows:

Deflection at end of bay 3 in Fife north cantilever, on east side ... ... = 1 in.
Ditto, ditto, on west side ... ... = $1\frac{1}{8}$,,

After this various trials were made with the trains running abreast at moderate speeds, and up to about 20 miles per hour. During these trials observations were taken of the deflections to north or south, as the case might be, of the tops of the vertical columns with the passage of the heavy trains. The observations were taken by means of theodolites placed on the circular granite piers. Referring again to the various positions of the trains as above, the movements noted were as follows:—

						in.
First position	:	not observed—see 6th position.				
Second ,,	:	Queensferry vertical columns	moved towards	north	... ...	2
,, ,,	:	Inchgarvie ,,	,, ,,	south	... ...	1
Third ,,	:	,, ,,	,, ,,	south	... ...	2
Fourth ,,	:	,, ,,	,, ,,	north	... ...	2
Fifth ,,	:	Fife ,,	,, ,,	south	... ...	2
Sixth ,,	:	,, ,,	,, ,,	north	... ...	1

From a suitable station near the old castle on Inchgarvie observations were also taken of the deflections of the end posts of the four free cantilevers during the passage at speed of heavy trains, and these agreed exactly with those obtained during the deadweight trials.

For testing the deflections in the central connecting girders two trains were made up, consisting each of three engines and six trucks at each end, these trains weighing 405 tons each, or a total weight of 810 tons upon each girder. Both in the north and south spans the application of this load produced a deflection of slightly over $1\frac{1}{2}$ in. at the centre of the girder.

The test loads applied to the 168 ft. spans of the approach viaducts produced deflections ranging from $\frac{11}{16}$ in. to $\frac{13}{16}$ in., or a mean of $\frac{3}{4}$ in.

Various special trials with trains running in opposite directions, and meeting each other at specified points, also took place.

The atmospheric conditions during the three days were not of the most agreeable character—an extremely cold and stiff easterly breeze blowing the whole time, and terminating in the afternoon of the 3rd day in a storm of sleet and rain.

The report by the Board of Trade Inspectors issued on February 24, 1890, is of a highly satisfactory and complimentary character, and enters into every question of interest to the travelling public.

On March 4, 1890, during a violent gale which blew from the south west with a pressure of 20 lb. per square foot, the Prince of Wales closed the last rivet in the north central girder, and from the south port of the south cantilever end pier declared the bridge open. At the banquet which followed the ceremony, and to which nearly 600 guests had been invited, the Prince of Wales announced that the Queen had conferred upon the Chairman of the Forth Bridge Company, Mr. Matthew William Thompson, and upon Sir John Fowler, K.C.M.G., the honour of baronetcies; upon Mr. Benjamin Baker the honour of K.C.M.G.; and upon Mr. William Arrol, the honour of a knighthood.

Between five and six o'clock the same night two heavy goods trains passed over the bridge—one from north and one from south, and commencing from the morning of the following day, Wednesday, 5th March—when passenger traffic between Dunfermline and Edinburgh was established—between 40 and 50 trains have been run every day and night over the now completed Forth Bridge.

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THE FORTH

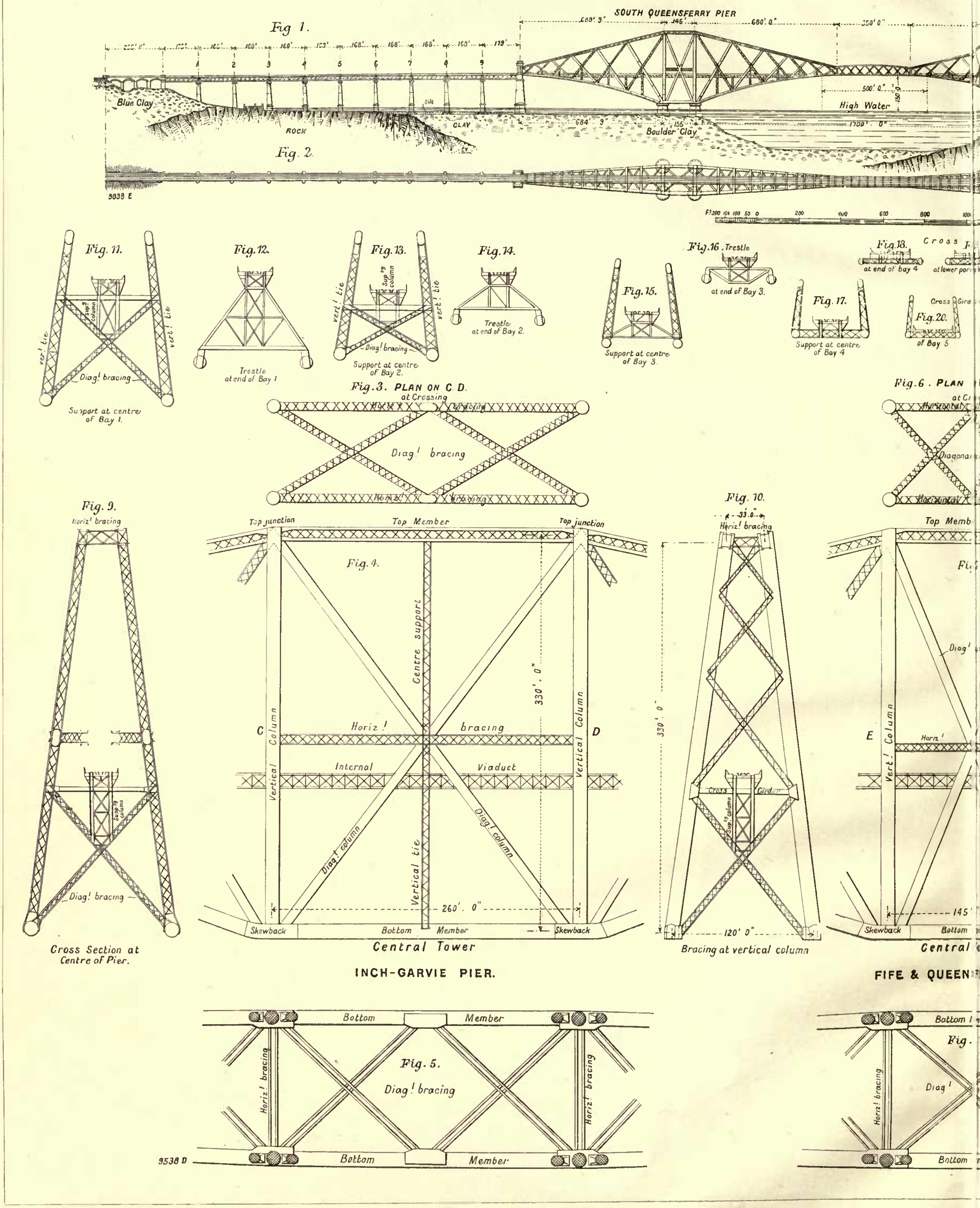
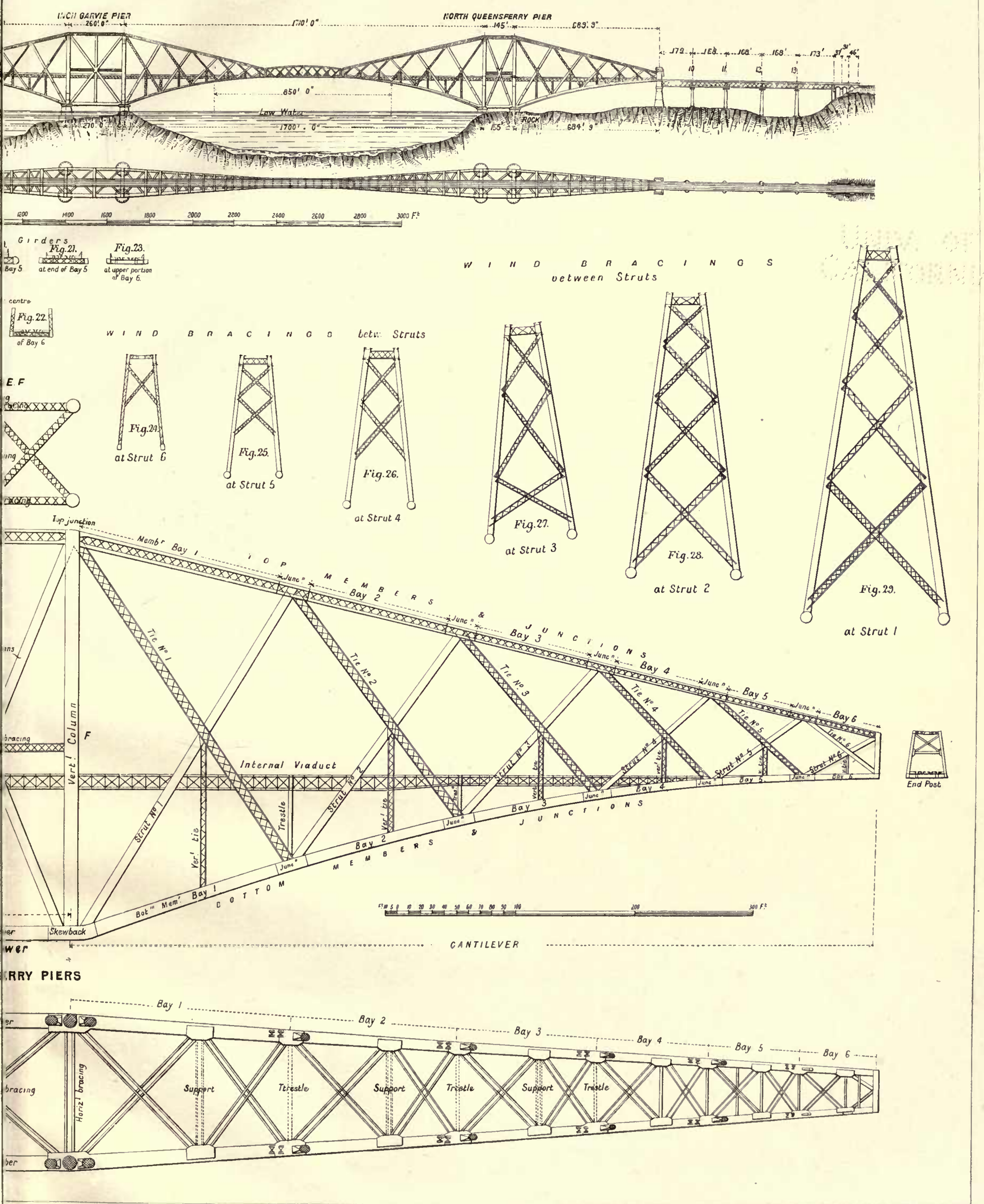
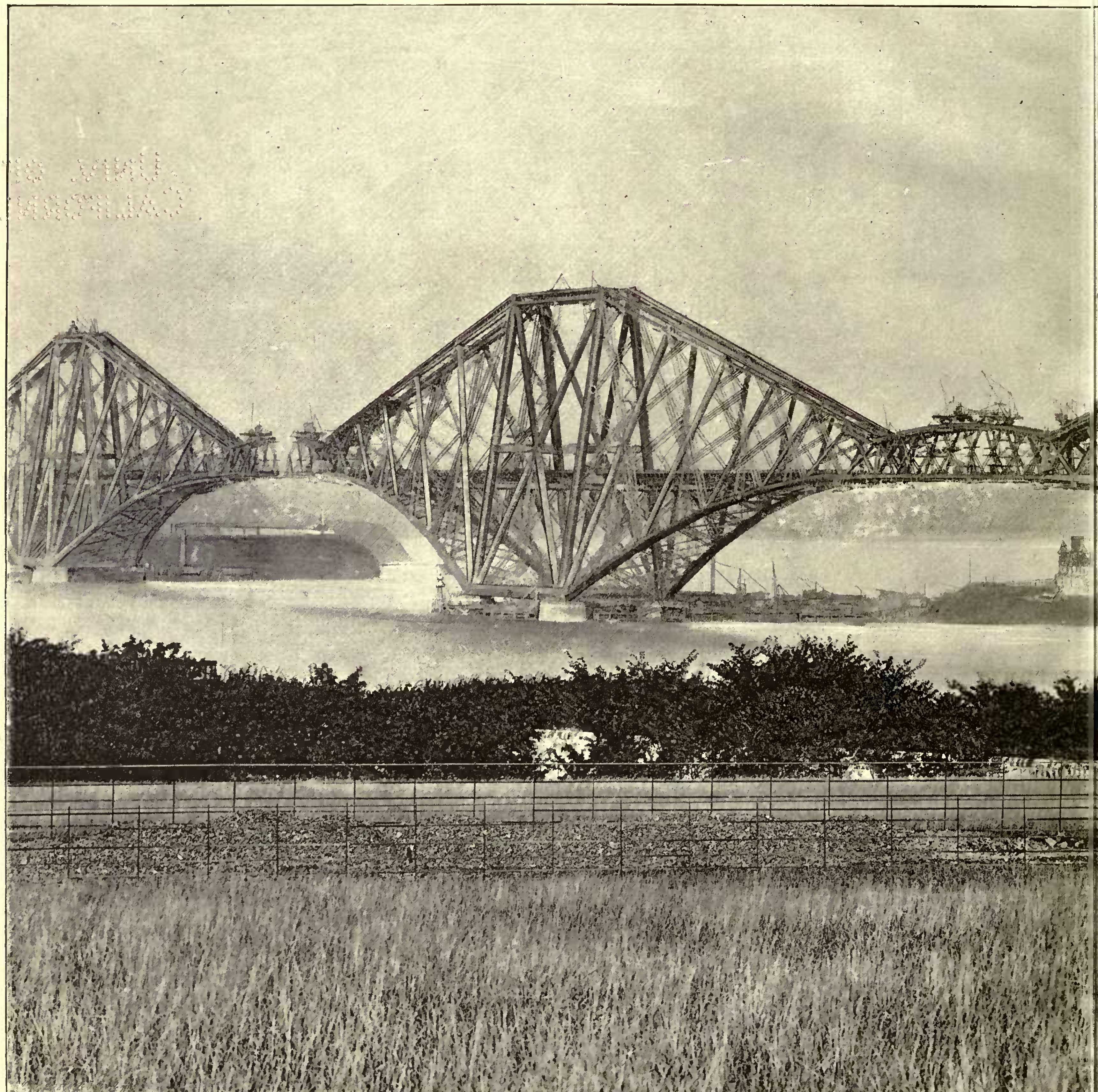


Fig. 1.
SOUTH QUEENSFERRY PIER
Blue Clay
ROCK
CLAY
Silt
Boulder Clay
High Water
Fig. 2.
9538 E
Fig. 11.
vert.l tie
Diag.l bracing
Support at centre of Bay 1.
Fig. 12.
Trestle at end of Bay 1
Fig. 13.
Diag.l bracing
Support at centre of Bay 2.
Fig. 14.
Trestle at end of Bay 2.
Fig. 15.
Support at centre of Bay 3.
Fig. 16. Trestle at end of Bay 3.
Fig. 17.
Support at centre of Bay 4
Fig. 18.
at end of Bay 4
Fig. 20.
of Bay 5
Fig. 3. PLAN ON C D.
at Crossing
Diag.l bracing
Fig. 6. PLAN
Fig. 9.
Horiz.l bracing
Diag.l bracing
Cross Section at Centre of Pier.
Fig. 4.
Top junction
Top Member
Centre support
330'. 0"
C
D
Vertical Column
Horiz.l bracing
Internal Viaduct
Diag.l column
Vertical tie
260'. 0"
Skewback
Bottom Member
Central Tower
INCH-GARVIE PIER.
Fig. 10.
33.0
Horiz.l bracing
330'. 0"
Cross Girder
120'. 0"
Bracing at vertical column
E
Vert.l Column
Central
FIFE & QUEEN
Fig. 5.
Diag.l bracing
Horiz.l bracing
Bottom Member
9538 D

H BRIDGE.

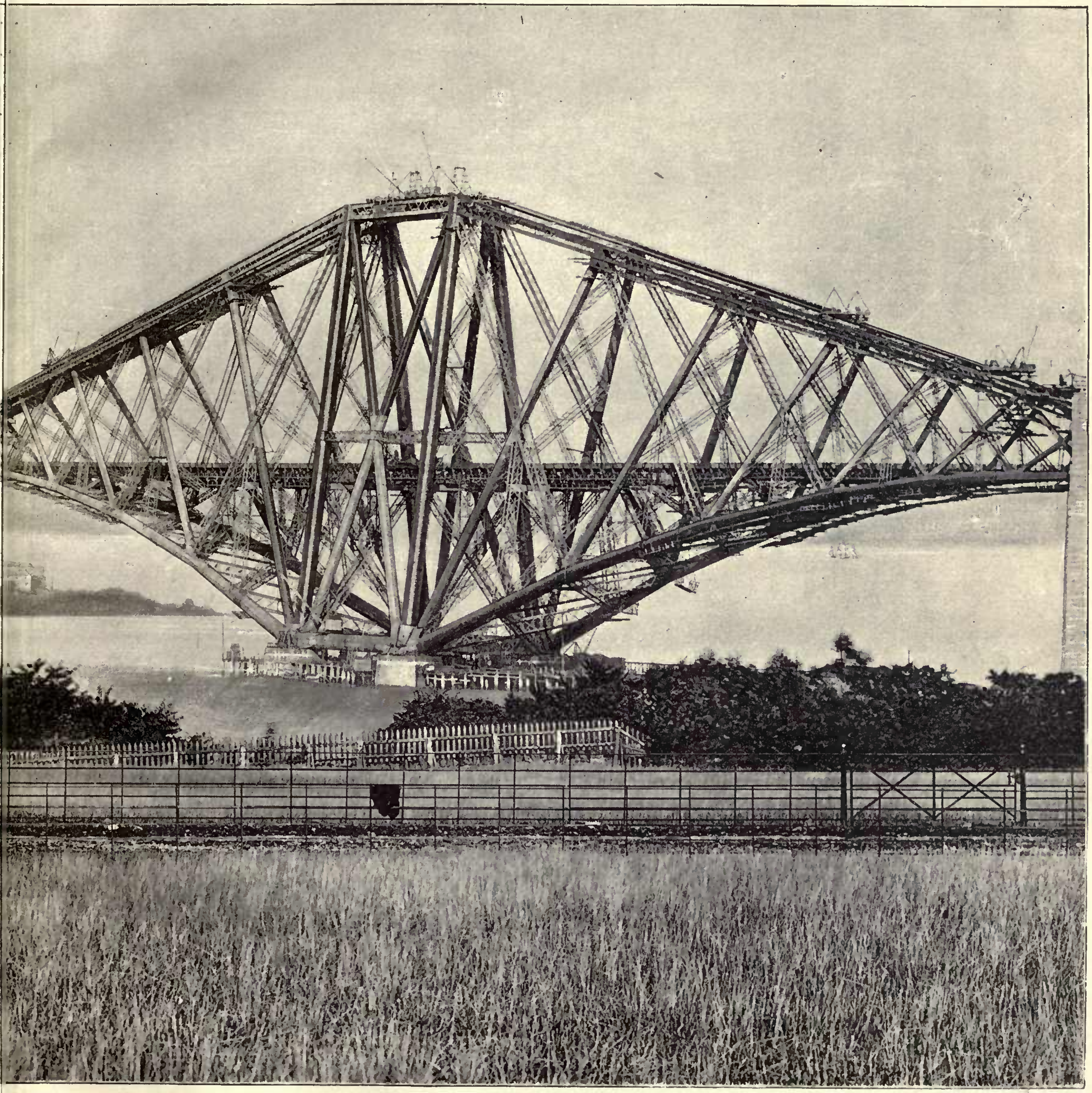

INCH GARVIE PIER
260' 0"
1710' 0"
NORTH QUEENSFERRY PIER
145'
689' 9"
179
168
168'
168'
173'
850' 0"
Low Water
270' 0"
1700' 0"
145
ROCK
689' 9"
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000 Ft.
Girders
Fig. 21.
Bay 5
at end of Bay 5
Fig. 23.
at upper portion of Bay 6.
Fig. 22.
of Bay 6
WIND BRACINGS between Struts
WIND BRACINGS between Struts
Fig. 24.
at Strut 6
Fig. 25.
at Strut 5
Fig. 26.
at Strut 4
Fig. 27.
at Strut 3
Fig. 28.
at Strut 2
Fig. 29.
at Strut 1
Top junction
TOP MEMBERS & JUNCTIONS
Bay 1
Bay 2
Bay 3
Bay 4
Bay 5
Bay 6
Tie No 1
Tie No 2
Tie No 3
Tie No 4
Tie No 5
Tie No 6
Vert.l Column
F
Internal Viaduct
Strut No 1
Strut No 2
Strut No 3
Strut No 4
Strut No 5
Strut No 6
Trestle
Vert.l tie
End Post
BOTTOM MEMBERS & JUNCTIONS
Bot.m Mem.r Bay 1
Skewback
0
10
20
30
40
50
60
70
80
90
100
200
300 Ft.
CANTILEVER
RRY PIERS
Bay 1
Bay 2
Bay 3
Bay 4
Bay 5
Bay 6
Horiz.l bracing
Support
Trestle
Support
Trestle
Support
Trestle

THE FOR'I



GENERAL VIEW OF BRIDGE. SOUTH CENTRAL GIRDER CONNECTI

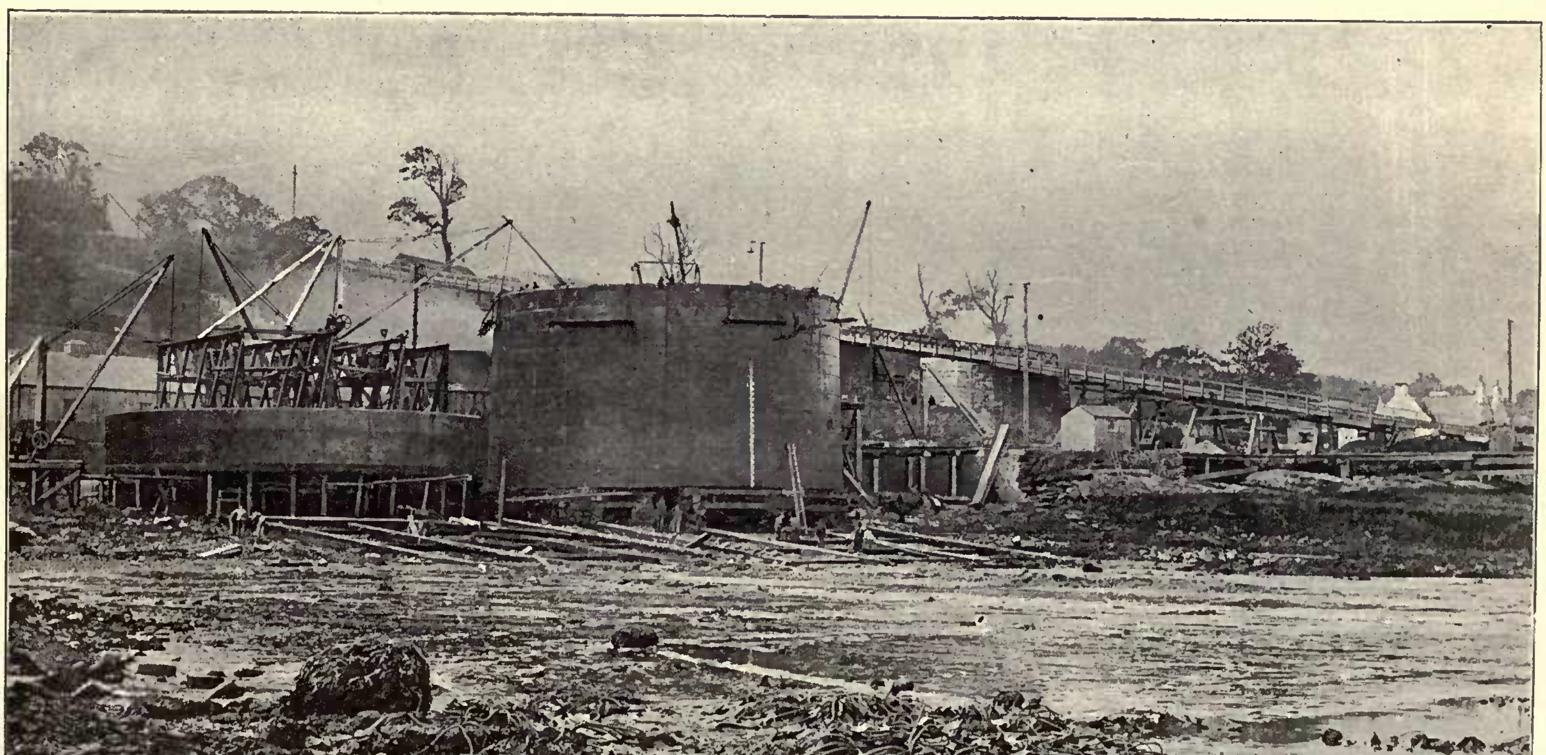
TH BRIDGE.



NORTH CENTRAL GIRDER NOT COMPLETED.

THE FORTH BRIDGE.

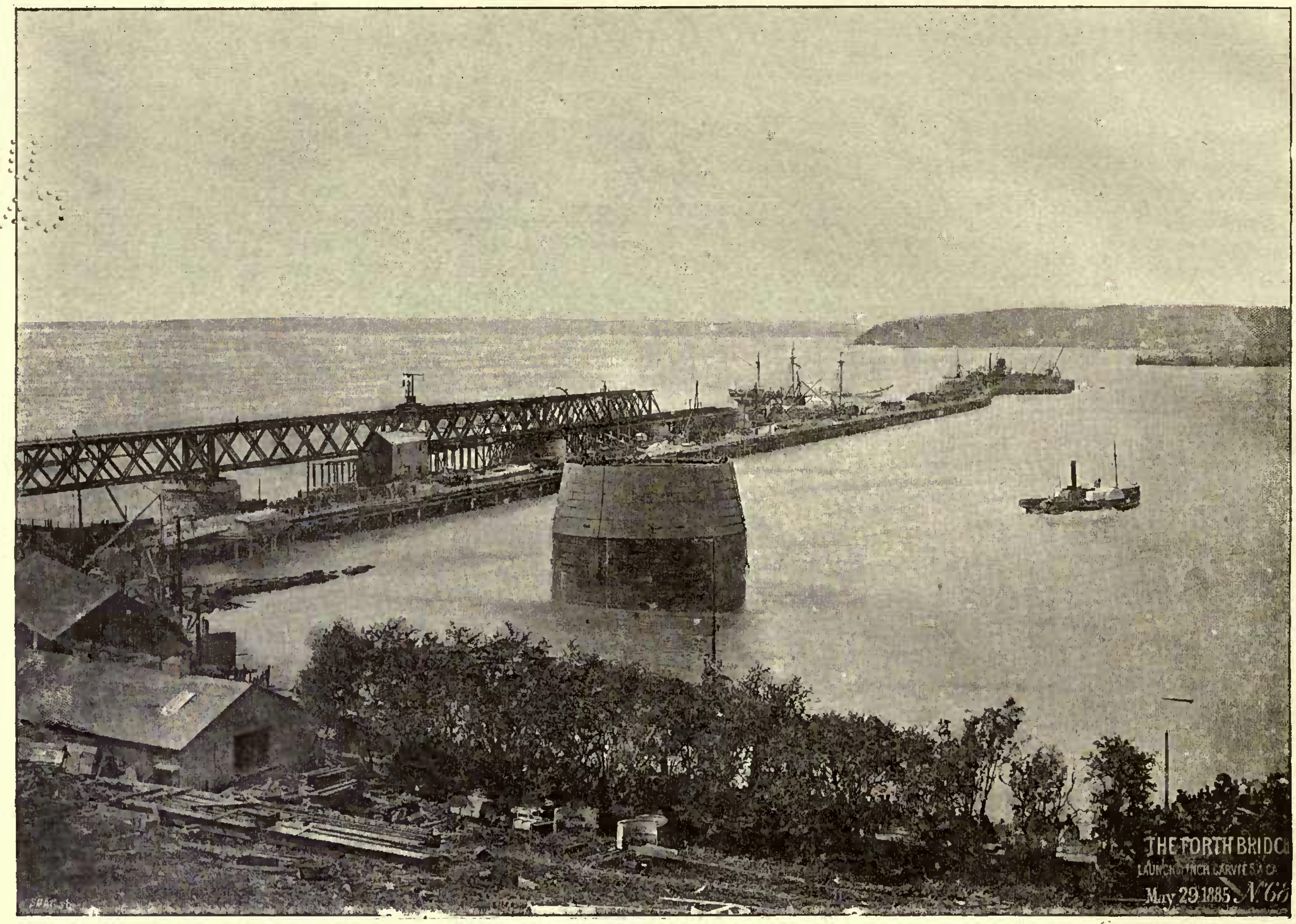
GENERAL VIEW OF SITE LOOKING NORTH-EAST.



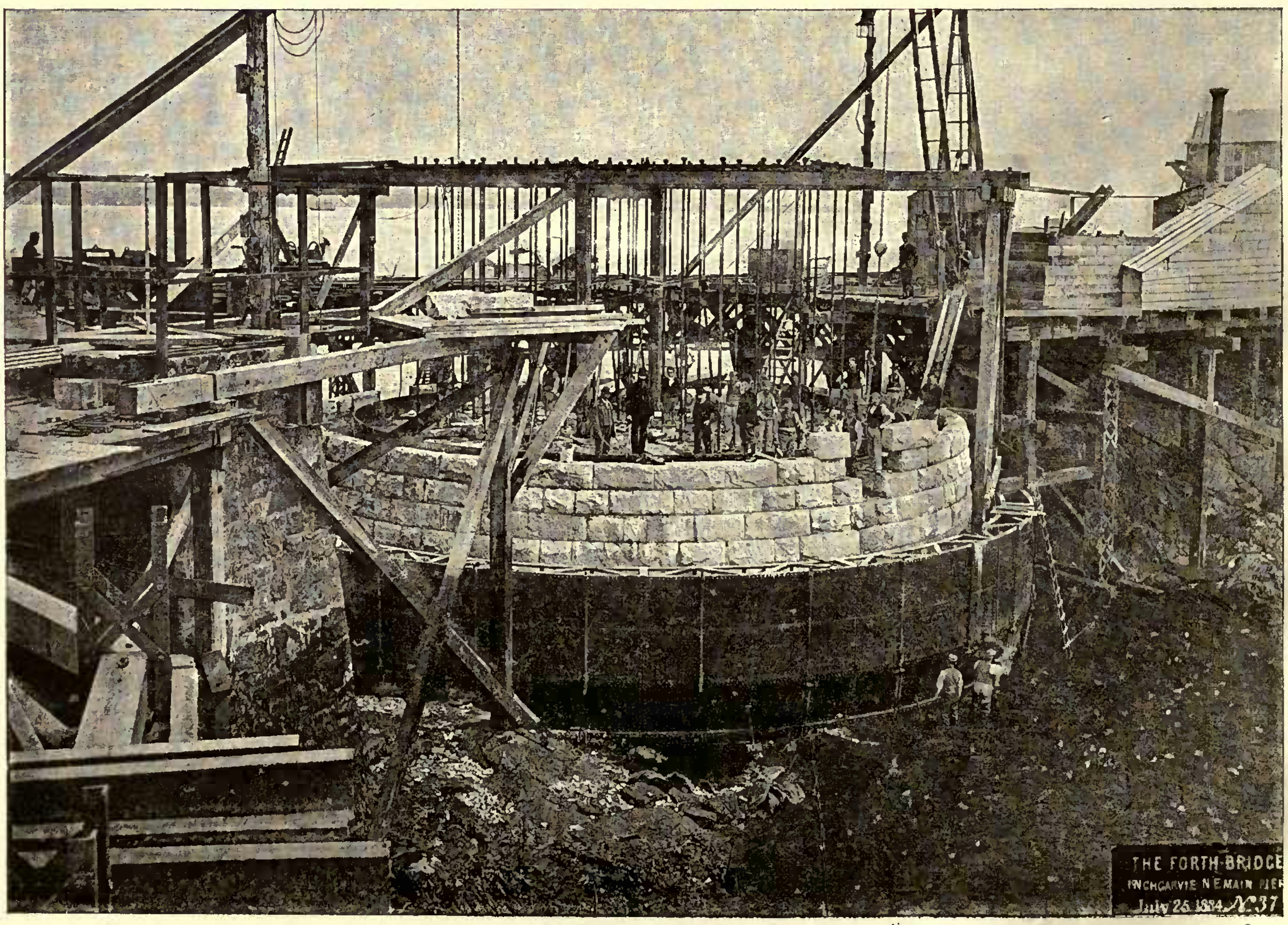
CAISSONS BUILDING ON LAUNCHING WAYS.

THE FORTH BRIDGE.

VIEW FROM INCHGARVIE CASTLE. THE SOUTH CAISSON IN POSITION

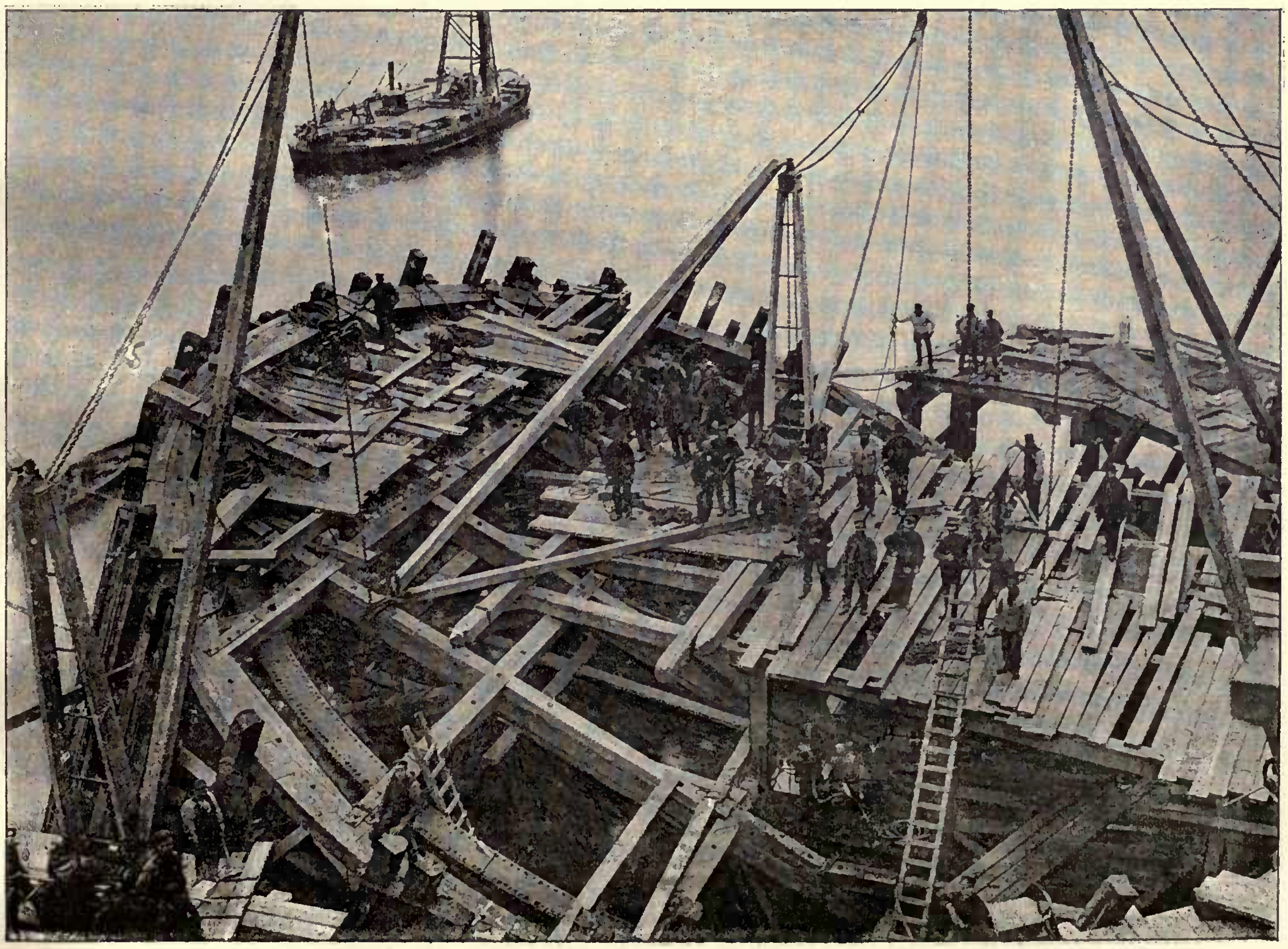


LAUNCHING OF CAISSON FOR SOUTH-WEST PIER, INCHGARVIE.



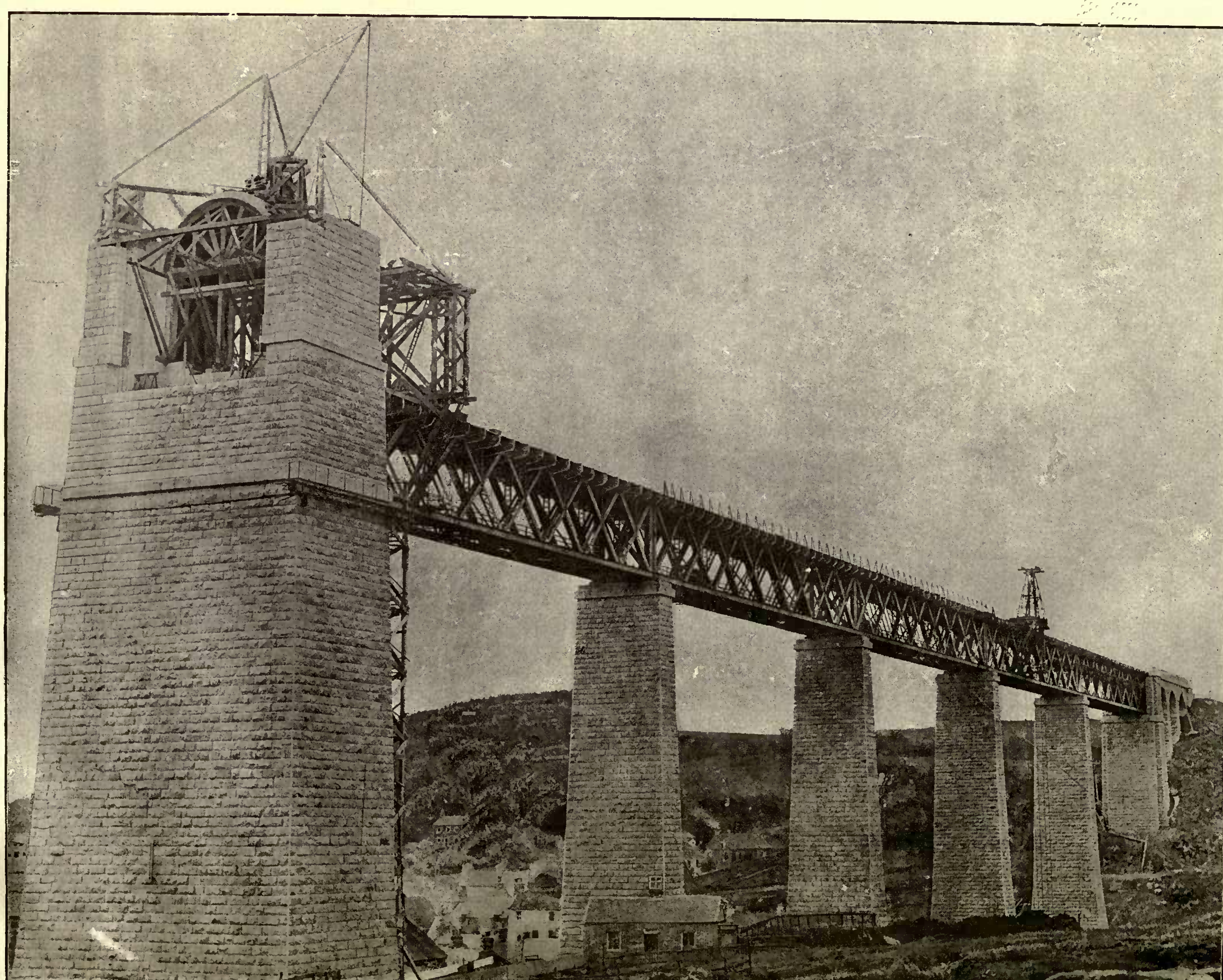
BUILDING OF NORTH-EAST CIRCULAR GRANITE PIER, INCHGARVIE.

GENERAL VIEW OF SITE, WITH PIERS OF SOUTH APPROACH VIADUCT, LOOKING NORTH.

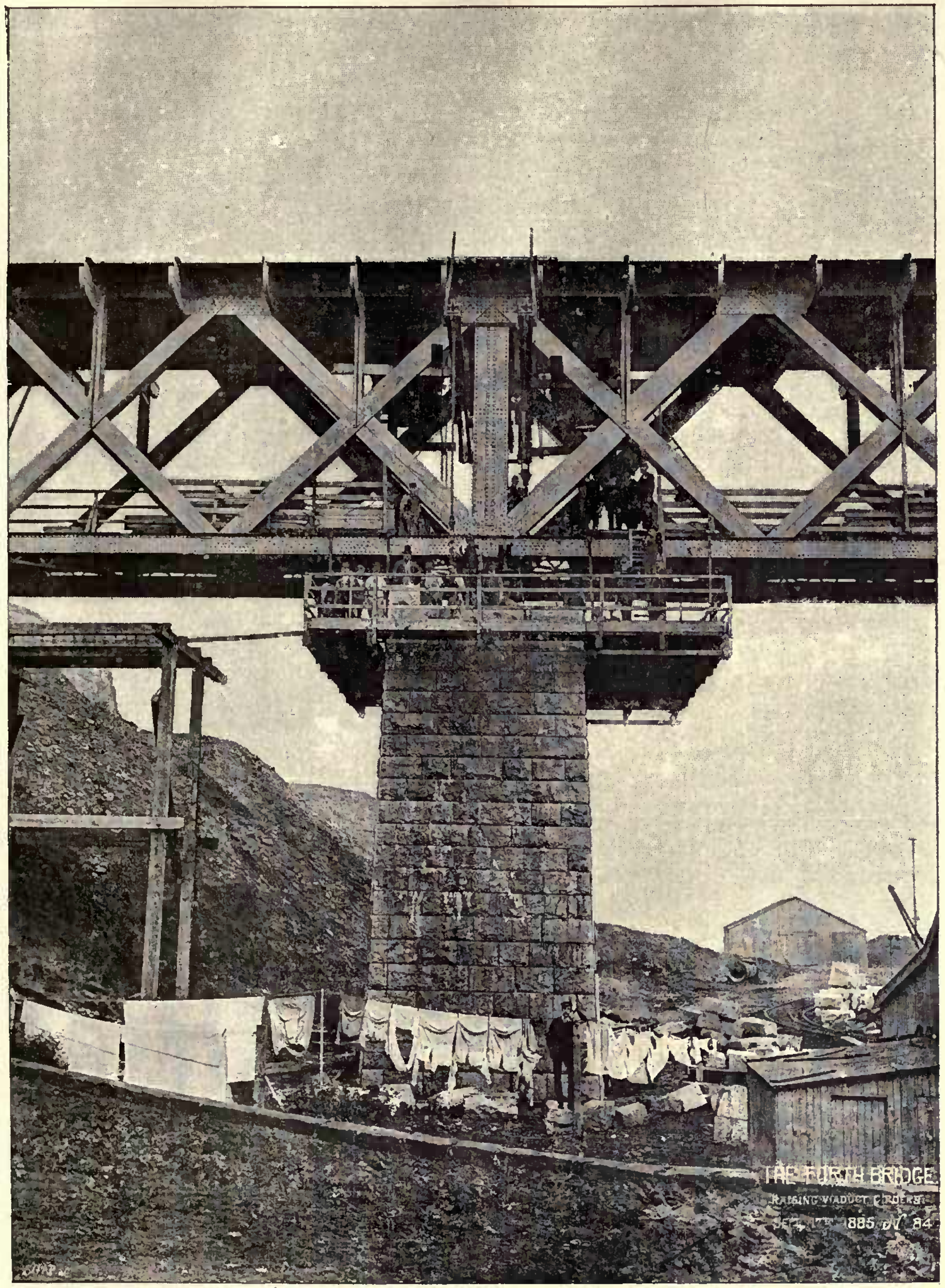


CAISSON FOR QUEENSFERRY NORTH-WEST PIER, CONSTRUCTING TIMBER CASING ROUND THE TILTED CAISSON.

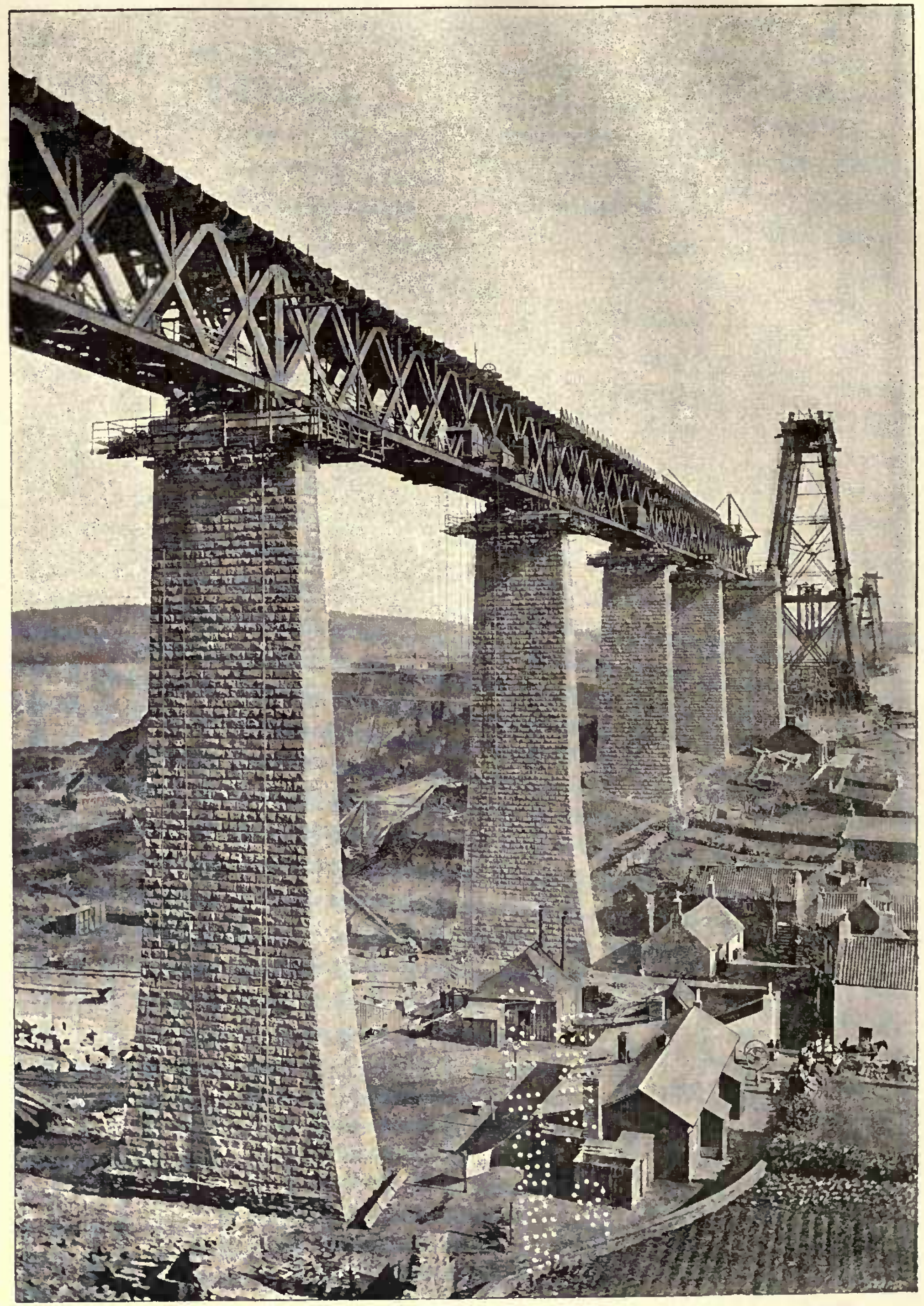
THE FORTH BRIDGE.



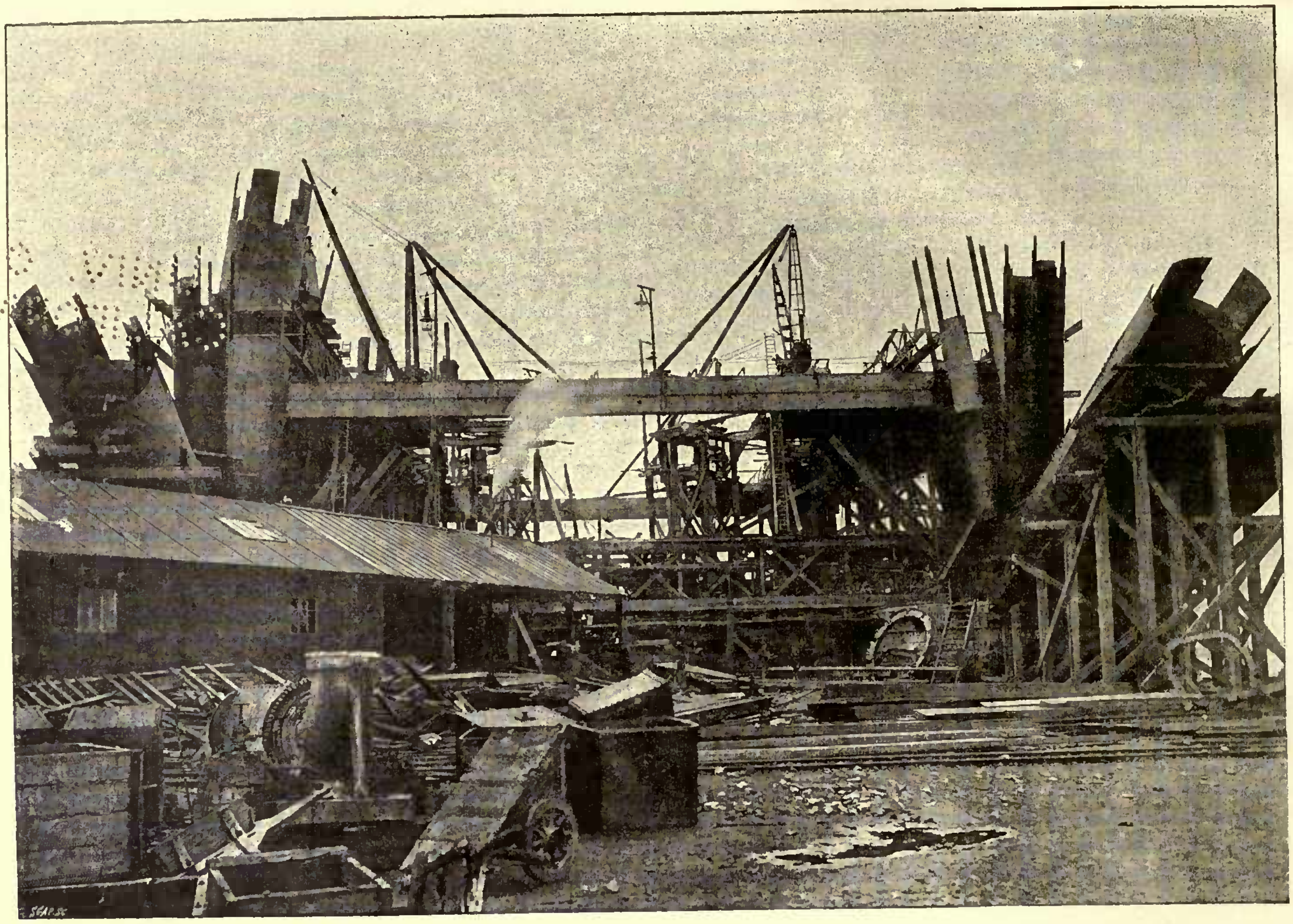
FRONT VIEW OF NORTH CANTILEVER END PIER AND VIEW OF VIADUCT AND ARCHES.



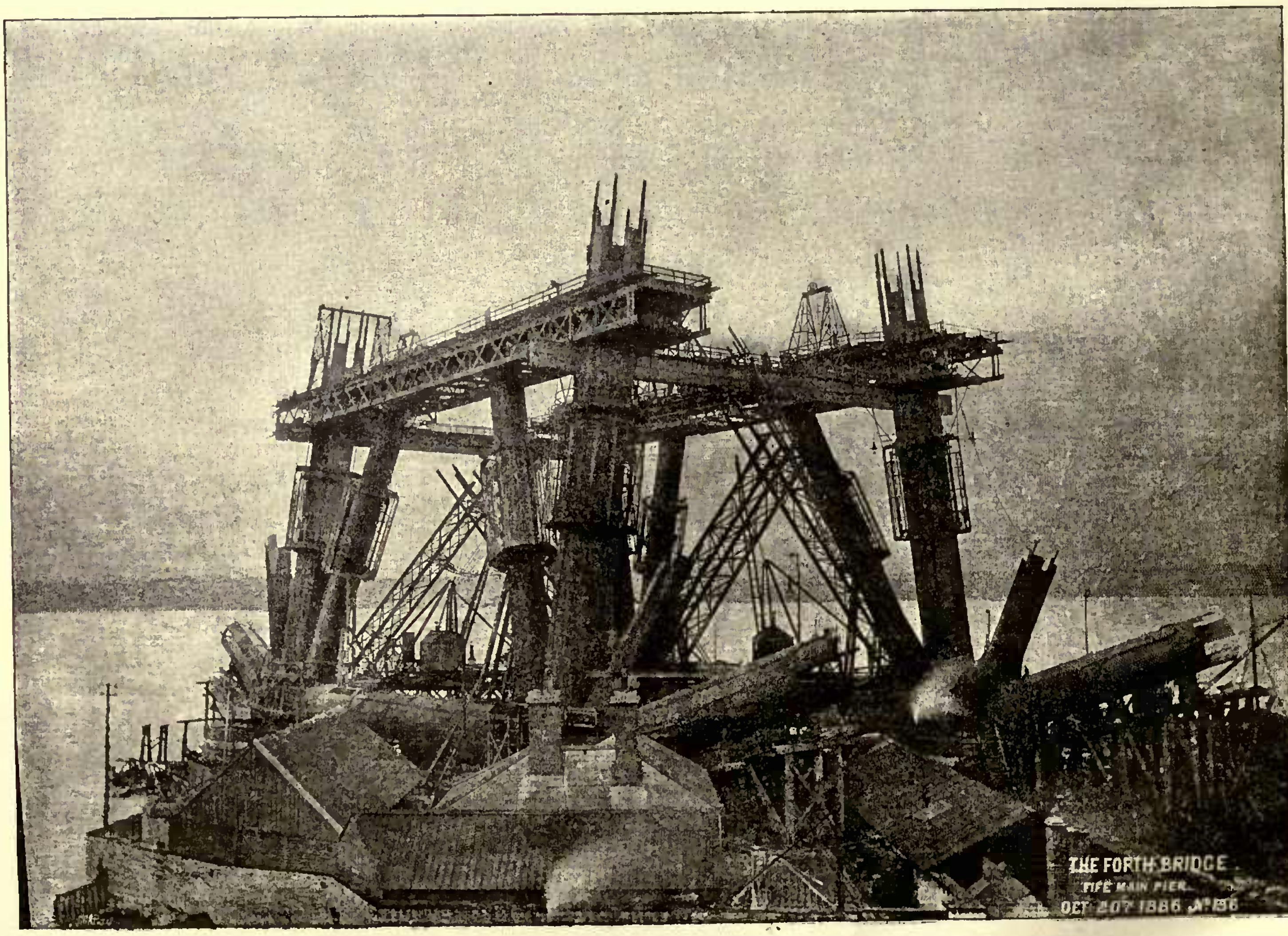
NORTH APPROACH VIADUCT; RAISING VIADUCT GIRDERS.



NORTH APPROACH VIADUCT; GIRDERS RAISED TO FULL HEIGHT.

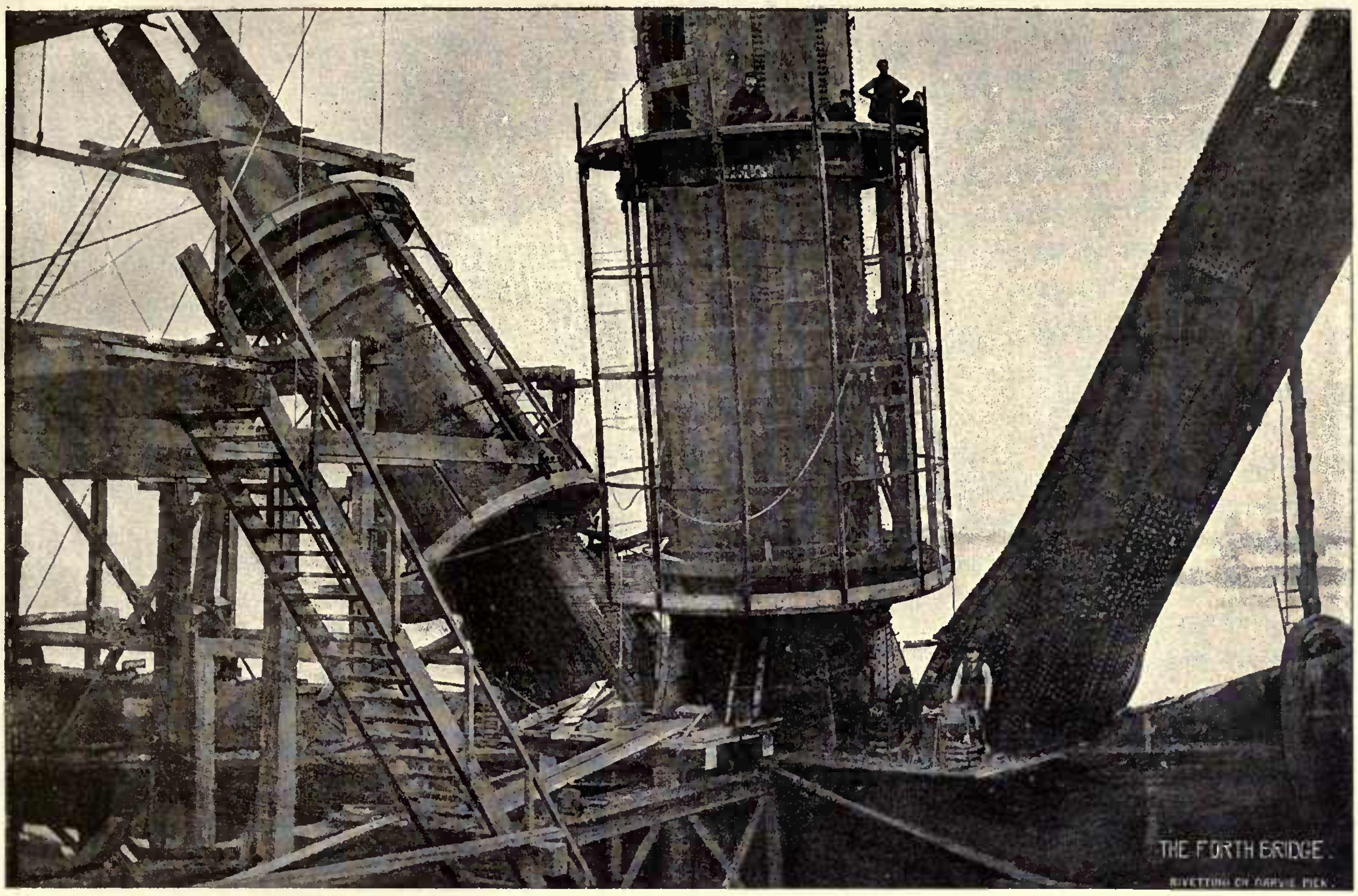


FIFE PIER. ERECTION OF SUPERSTRUCTURE ; CONSTRUCTION OF LIFTING PLATFORMS.

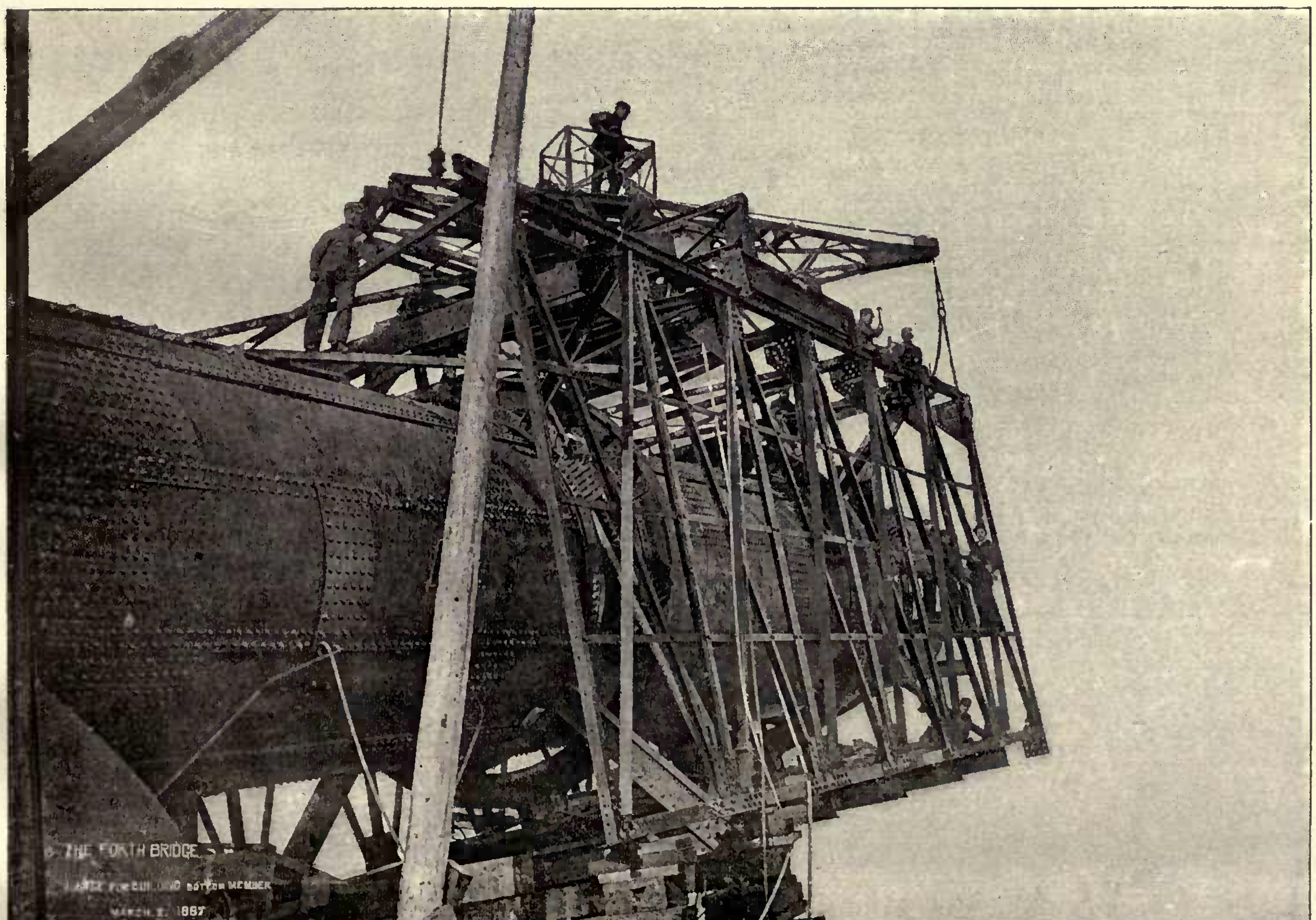


FIFE PIER. ERECTION OF SUPERSTRUCTURE ; LIFTING PLATFORMS ABOUT 100 FT. ABOVE HIGH WATER.

H BRIDGE.

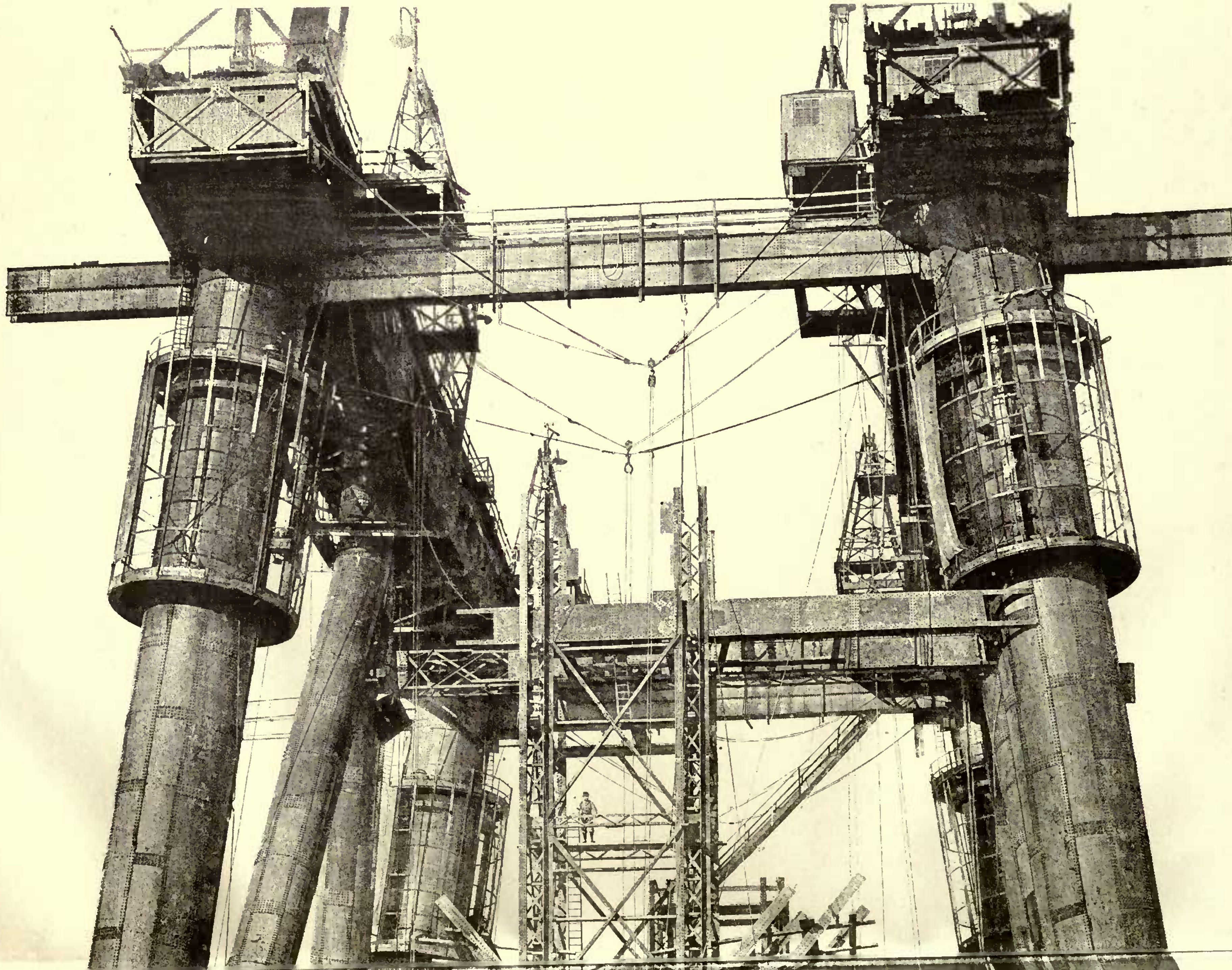


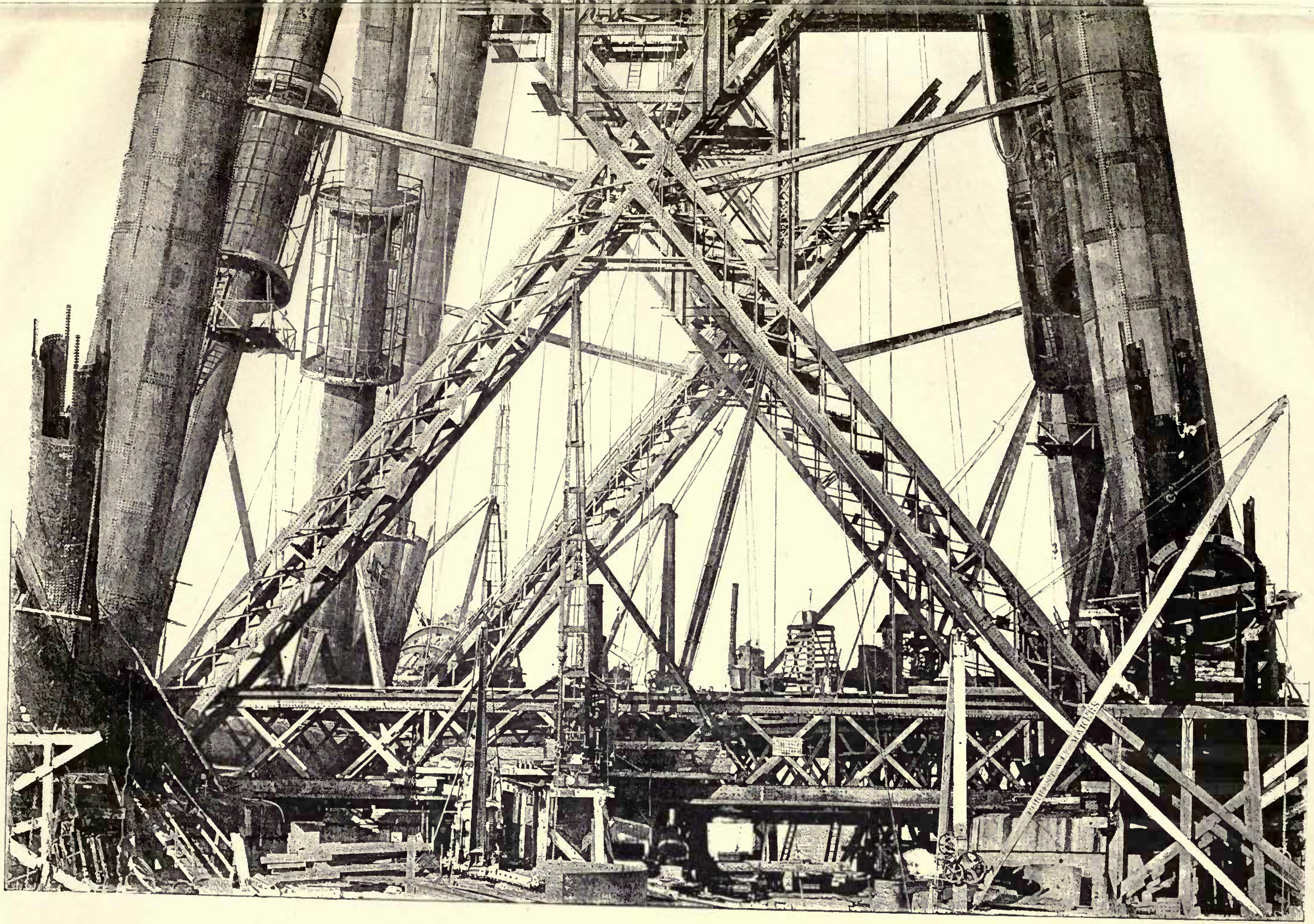
INCHGARVIE PIER. ERECTION OF SUPERSTRUCTURE ; RIVETTING CAGES AND HYDRAULIC RIVETTING MACHINES ON VERTICAL COLUMN AND DIAGONAL STRUT.



CAGE FOR BUILDING AND RIVETTING BOTTOM MEMBERS.

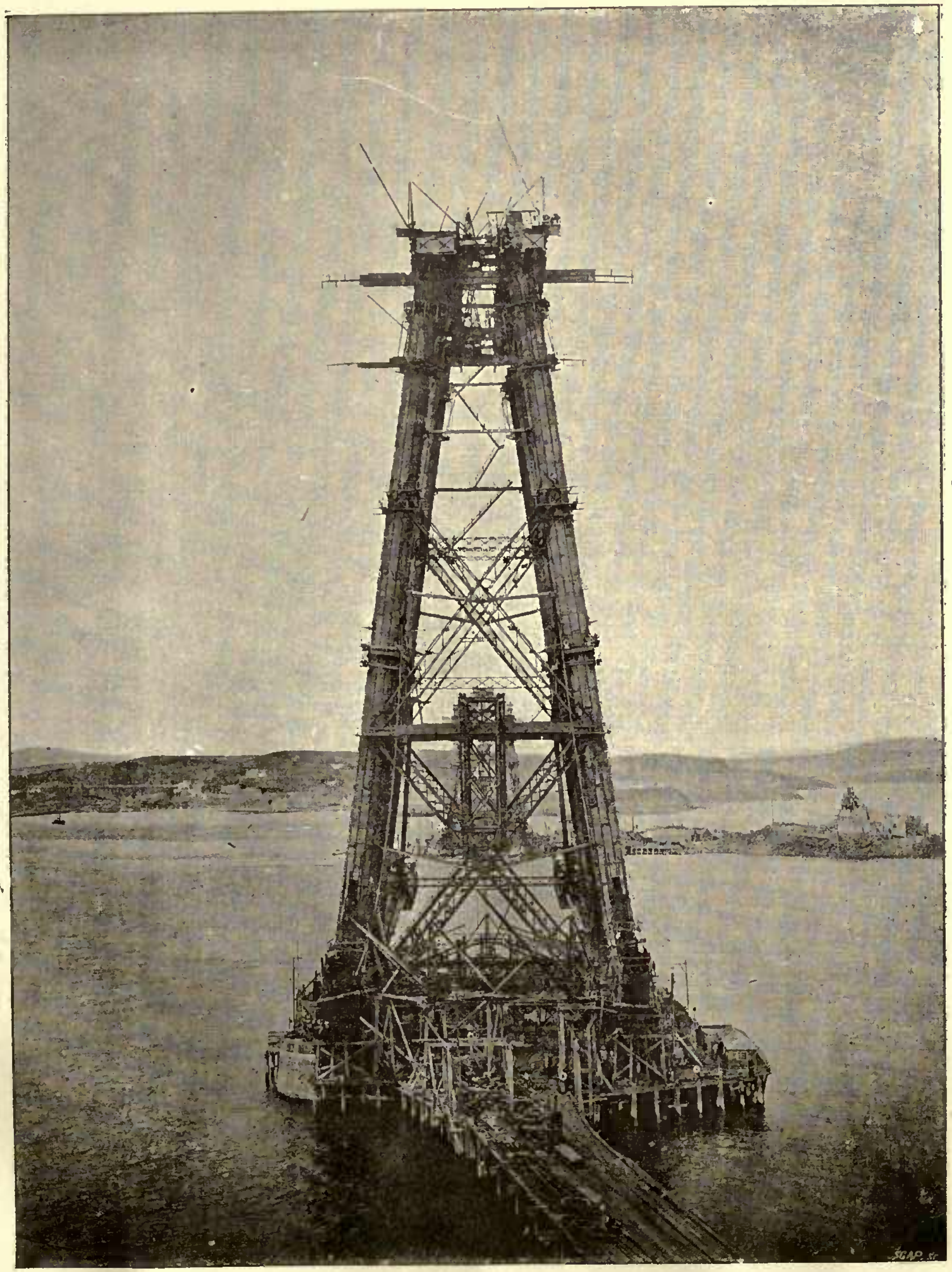
THE FORTH BRIDGE.



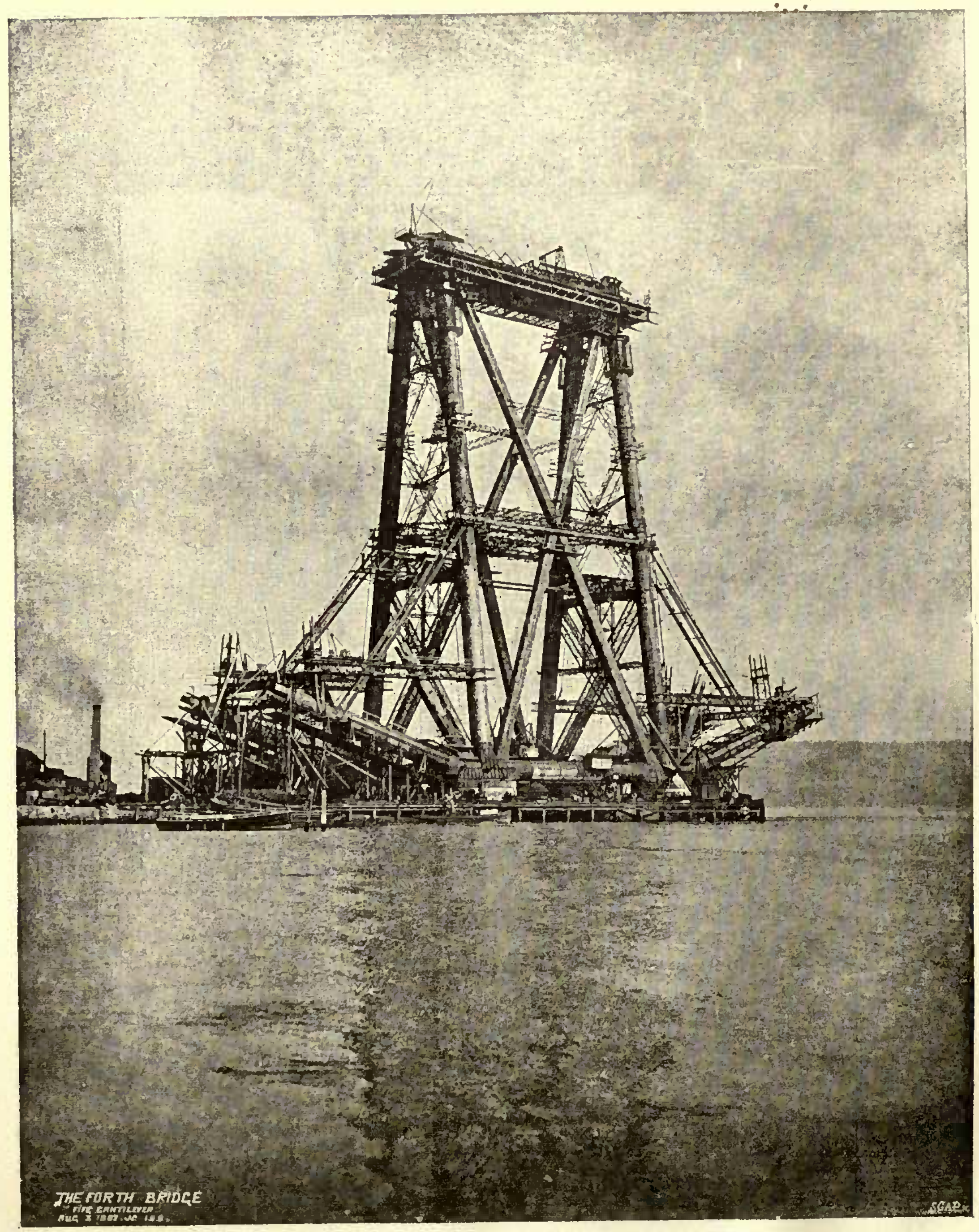


QUEENSFERRY PIER, LOOKING NORTH. LIFTINO PLATFORMS ABOUT 190 FT. ABOVE HIGH-WATER LEVEL.

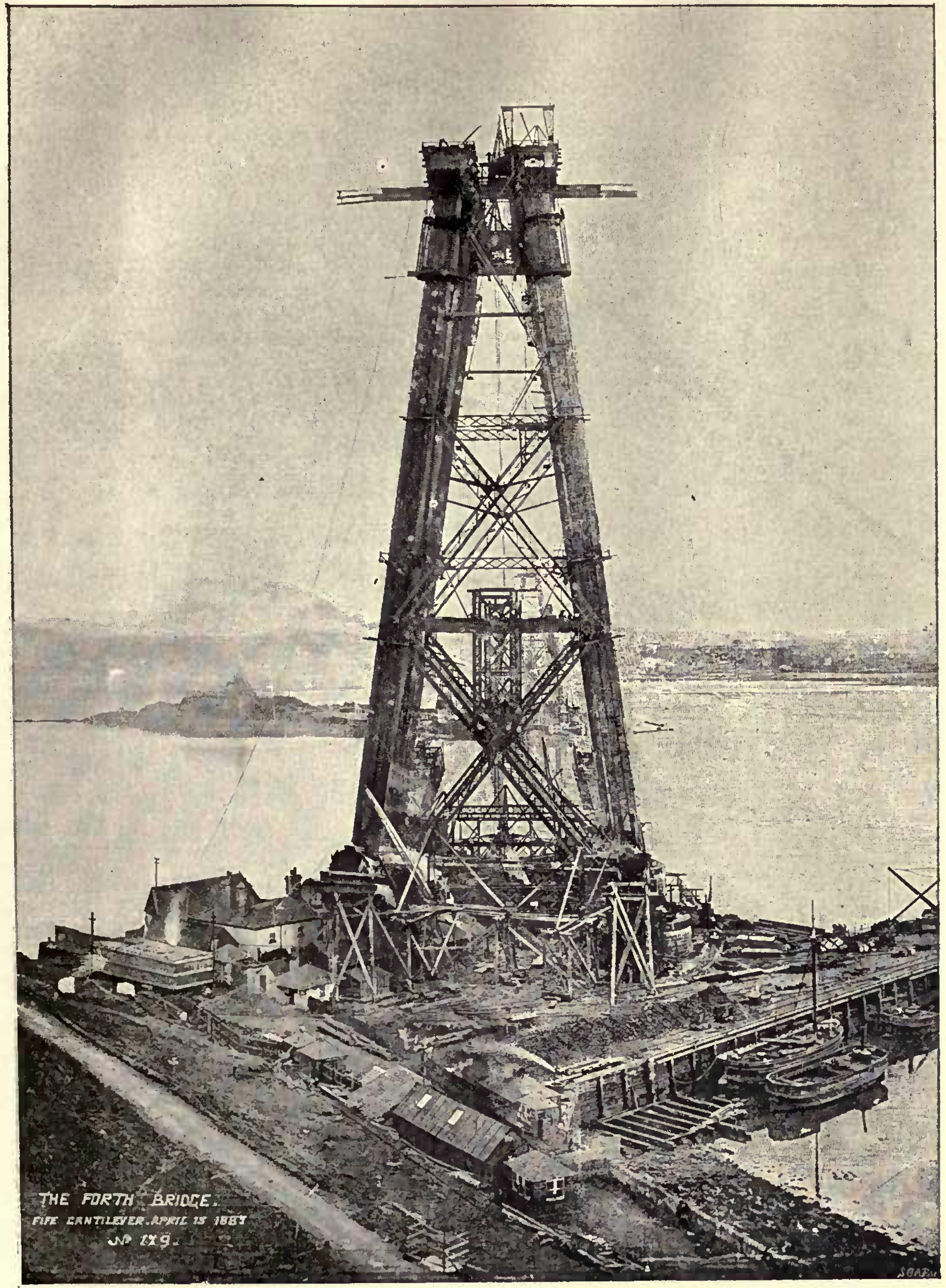
THE FORTH BRIDGE.



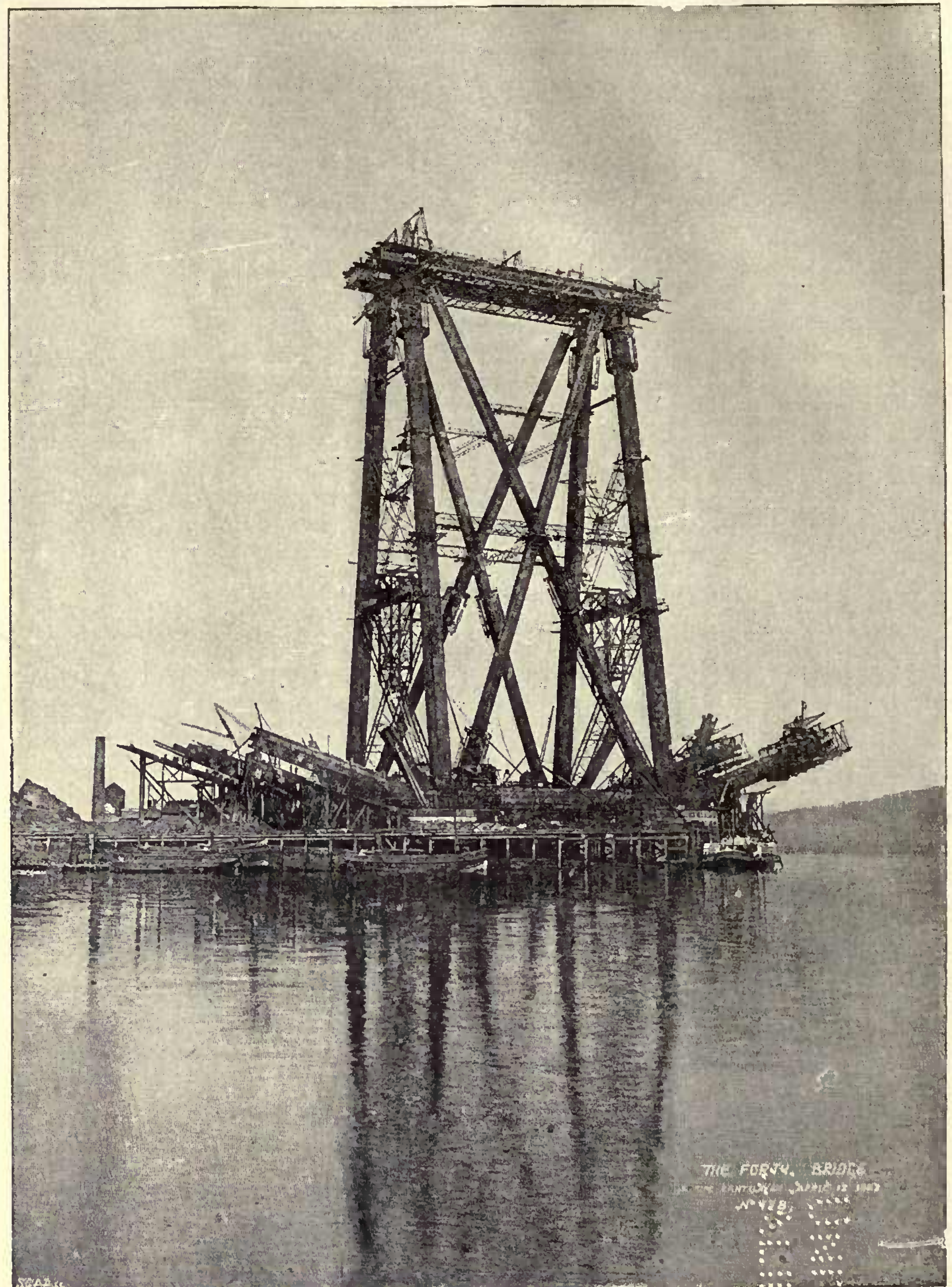
QUEENSFERRY PIER, LOOKING NORTH. PLATFORMS RAISED TO FULL HEIGHT.



FIFE PIER. BUILDING OF TOP MEMBERS ON PLATFORMS. COMMENCEMENT OF BUILDING OUT BOTTOM MEMBERS IN CANTILEVERS, AND SHOWING TEMPORARY SUPPORTS.

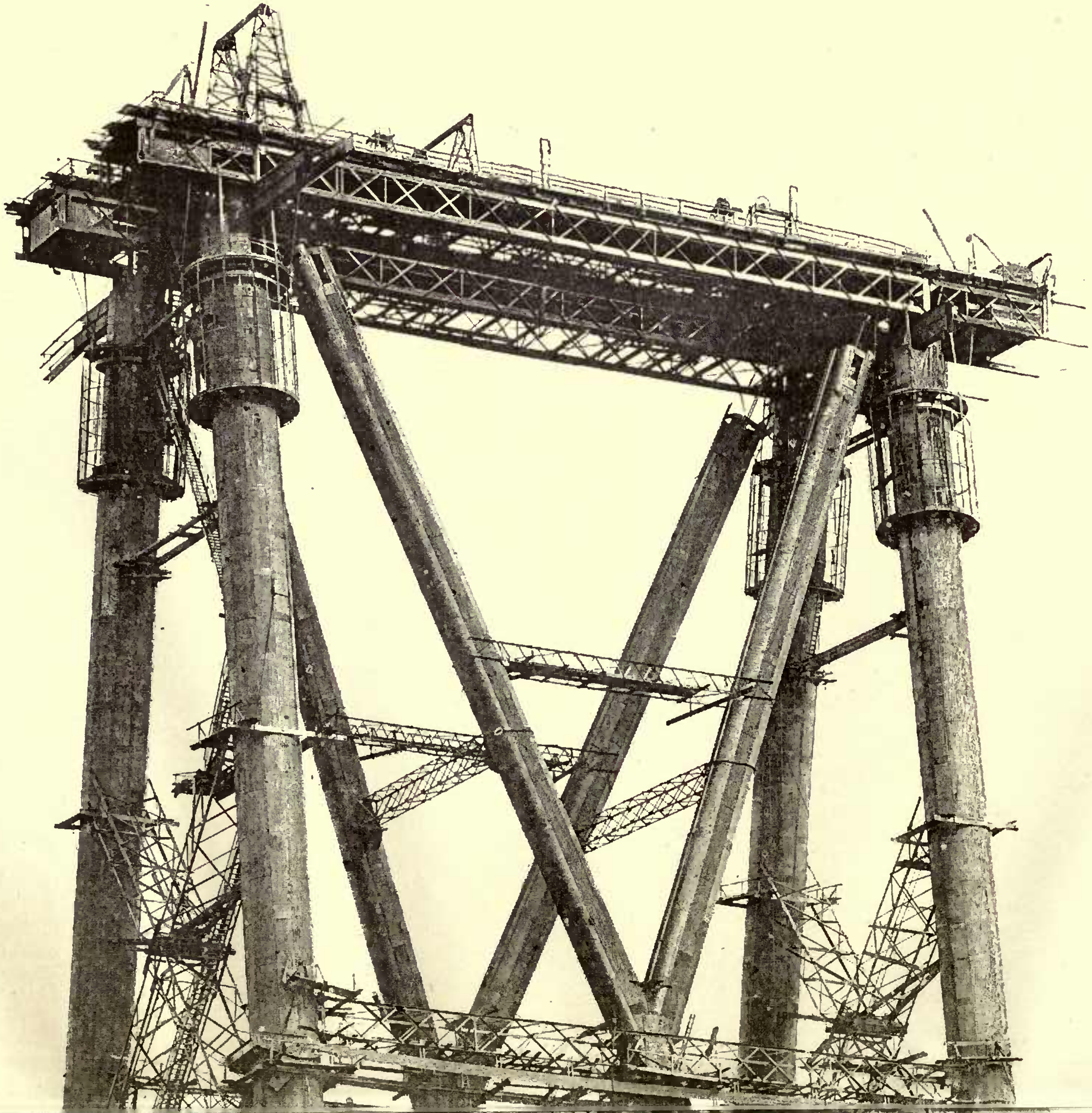


FIFE PIER, LOOKING SOUTH. PLATFORMS RAISED TO FULL HEIGHT.

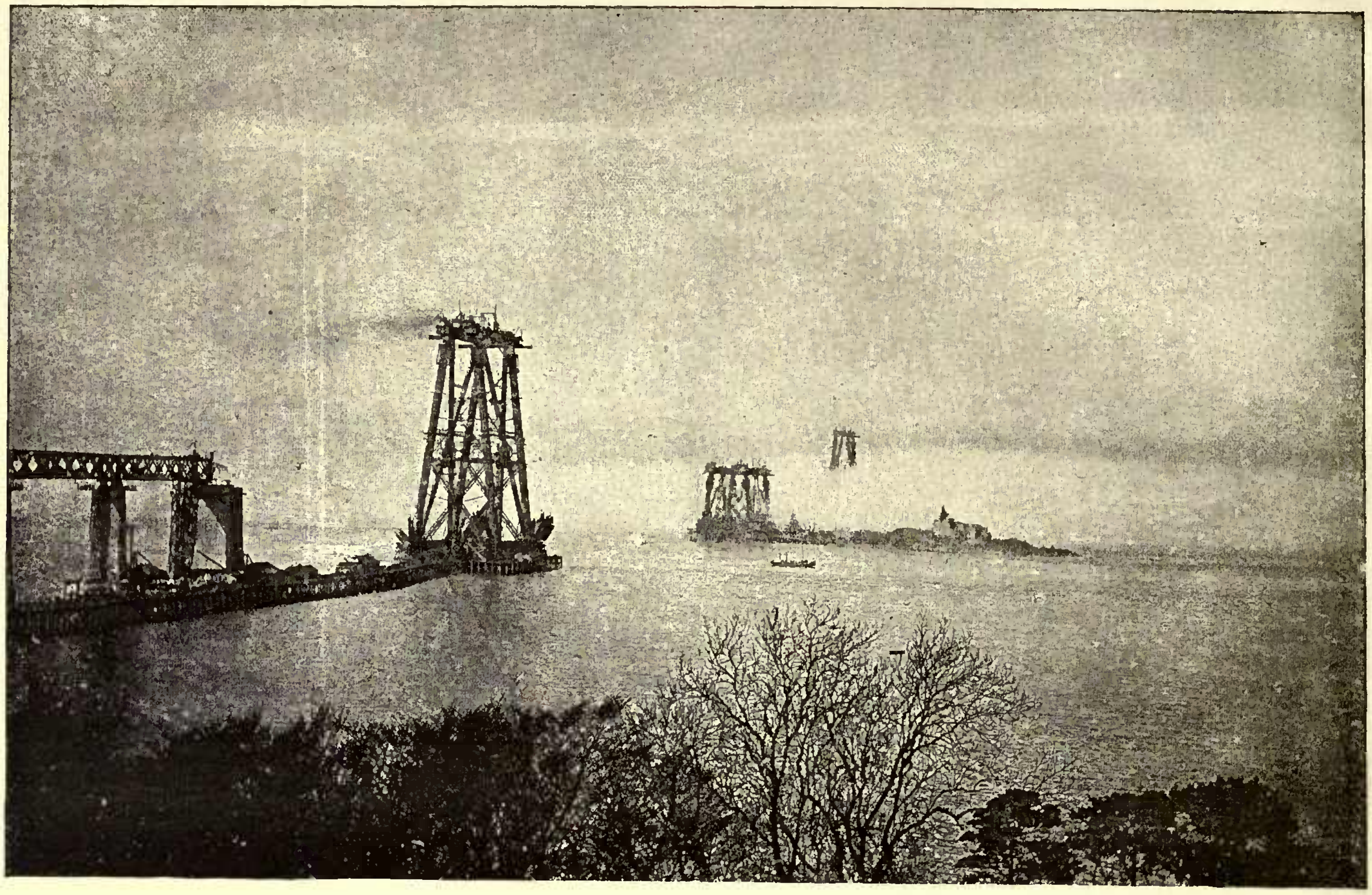


FIFE PIER. PLATFORMS RAISED TO FULL HEIGHT.

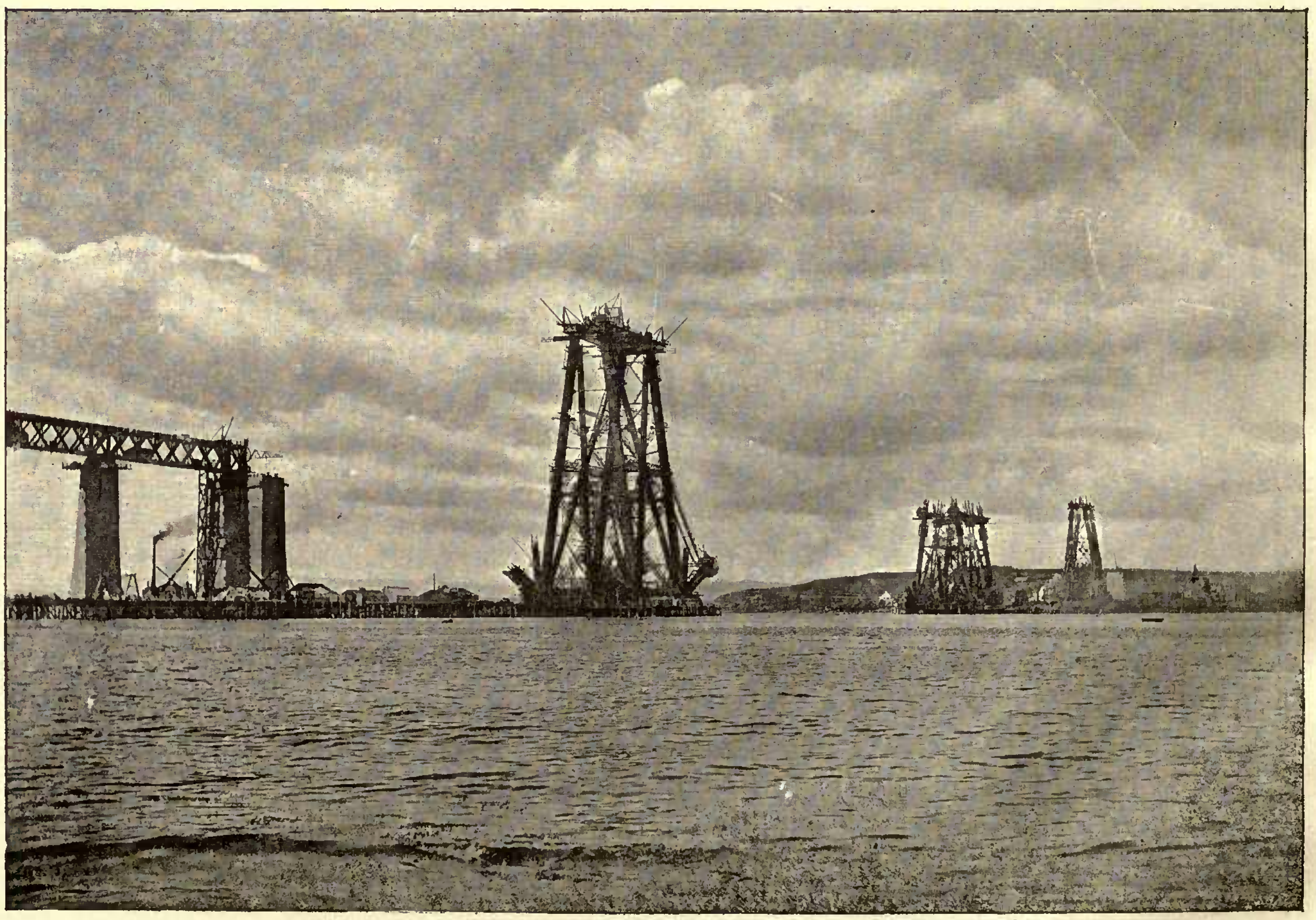
THE FORTH BRIDGE.



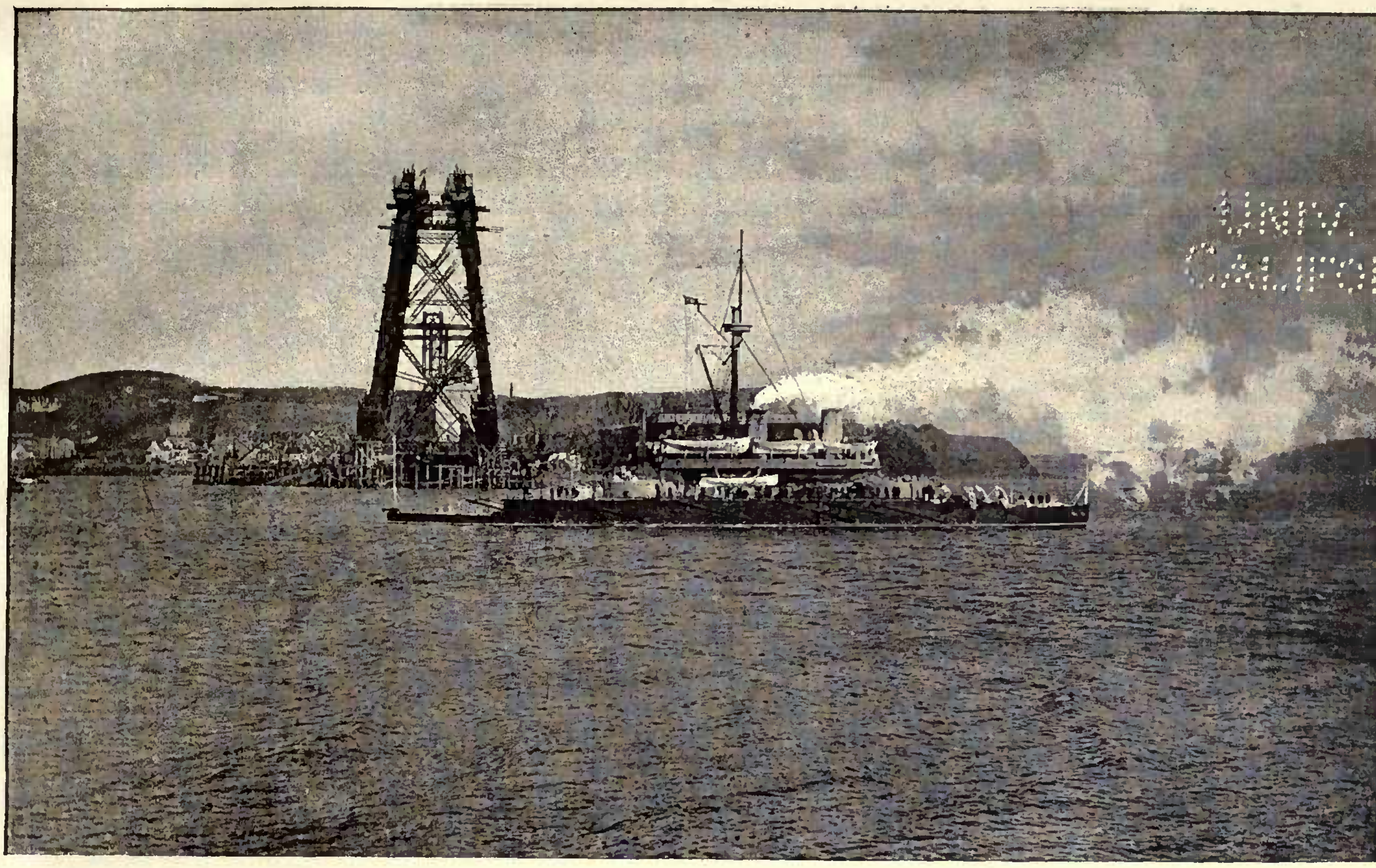
FIFE CANTILEVER. SIDE ELEVATION, LOOKING FAST.



EFFECT OF SEA FOG. CENTRAL TOWERS AND SOUTH APPROACH VIADUCT.



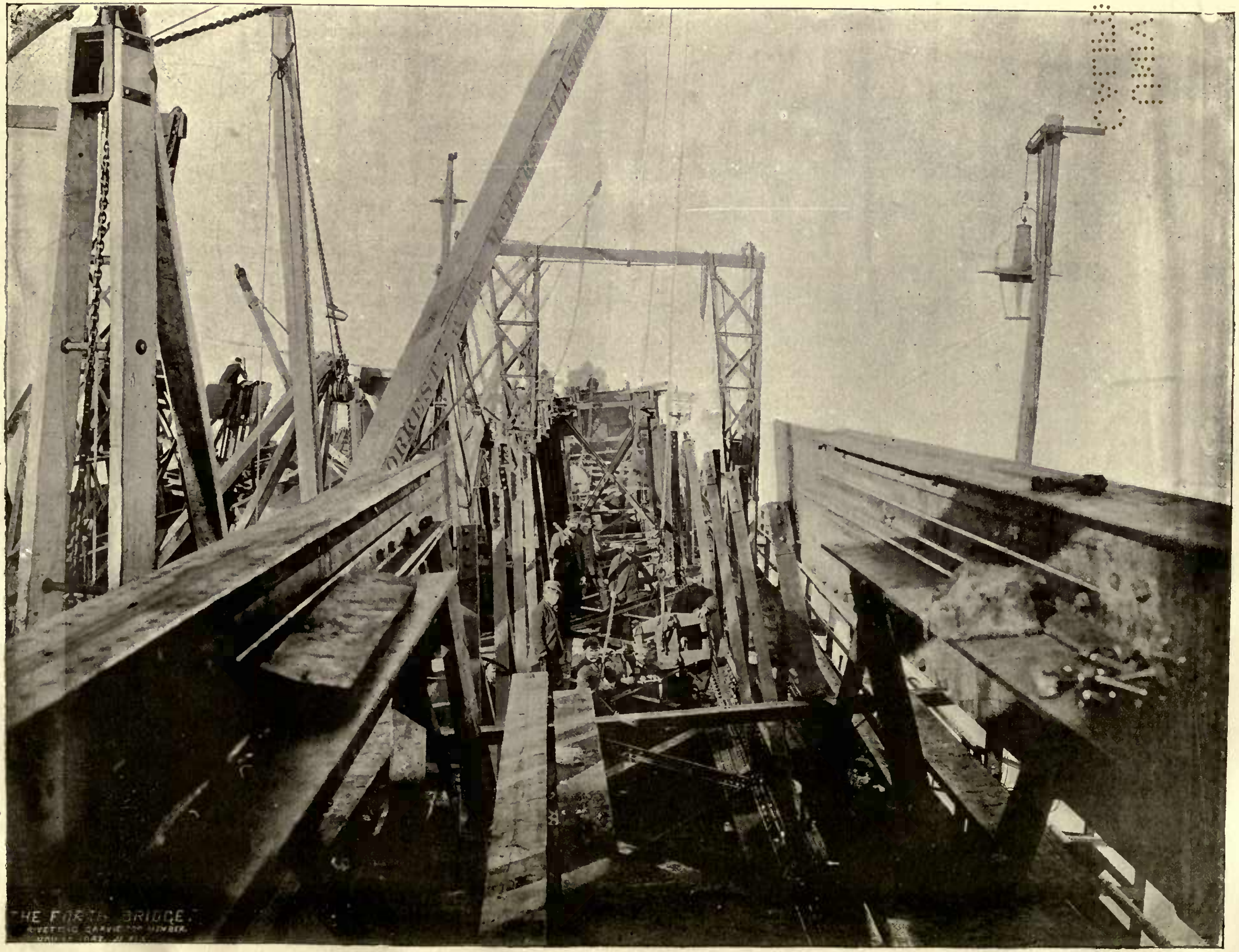
GENERAL VIEW OF CENTRAL TOWERS AND APPROACH VIADUCTS LOOKING NORTH.



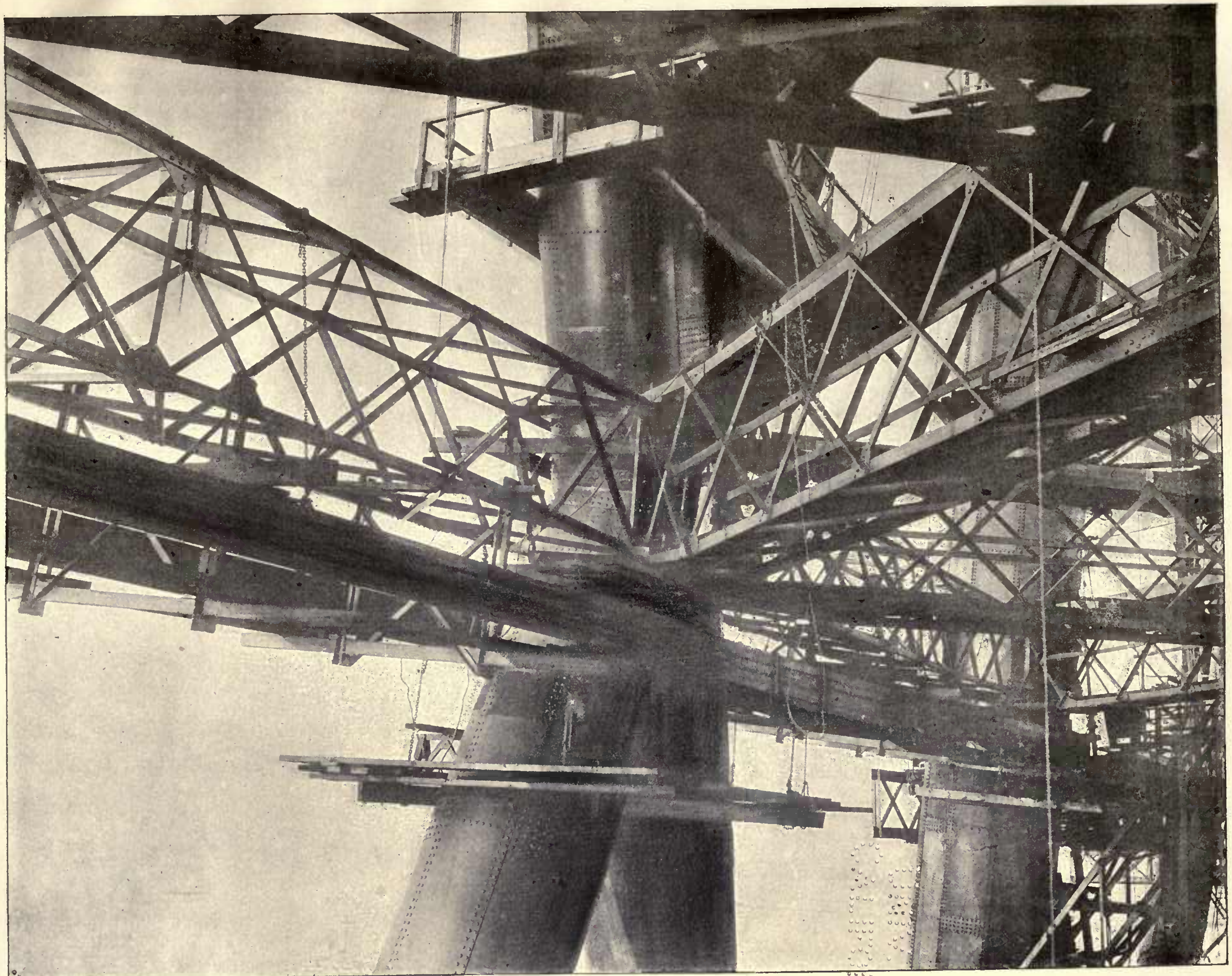
H.M.S. "DEVASTATION" PASSING THE FIFE PIER.

QUEENSFERRY NORTH-EAST PIER. PUTTING TOGETHER UPPER BEDPLATE.

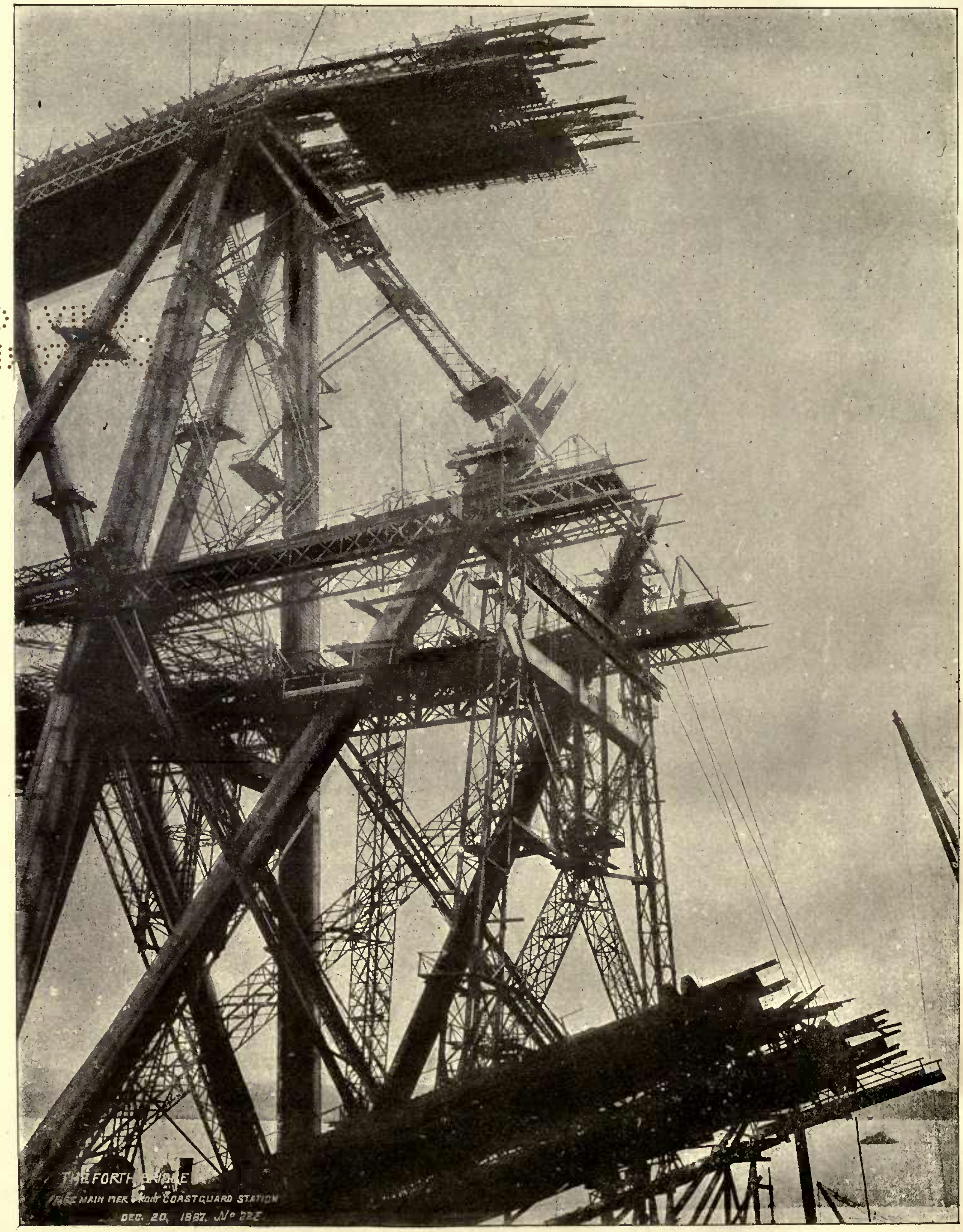
THE FORTH BRIDGE.



INCHGARVIE PIER. RIVETTING IN TOP MEMBERS BETWEEN VERTICAL COLUMNS.



QUEENSFERRY PIER. INTERSECTION OF DIAGONAL STRUTS, WITH HORIZONTAL AND DIAGONAL BRACING GIRDERS.

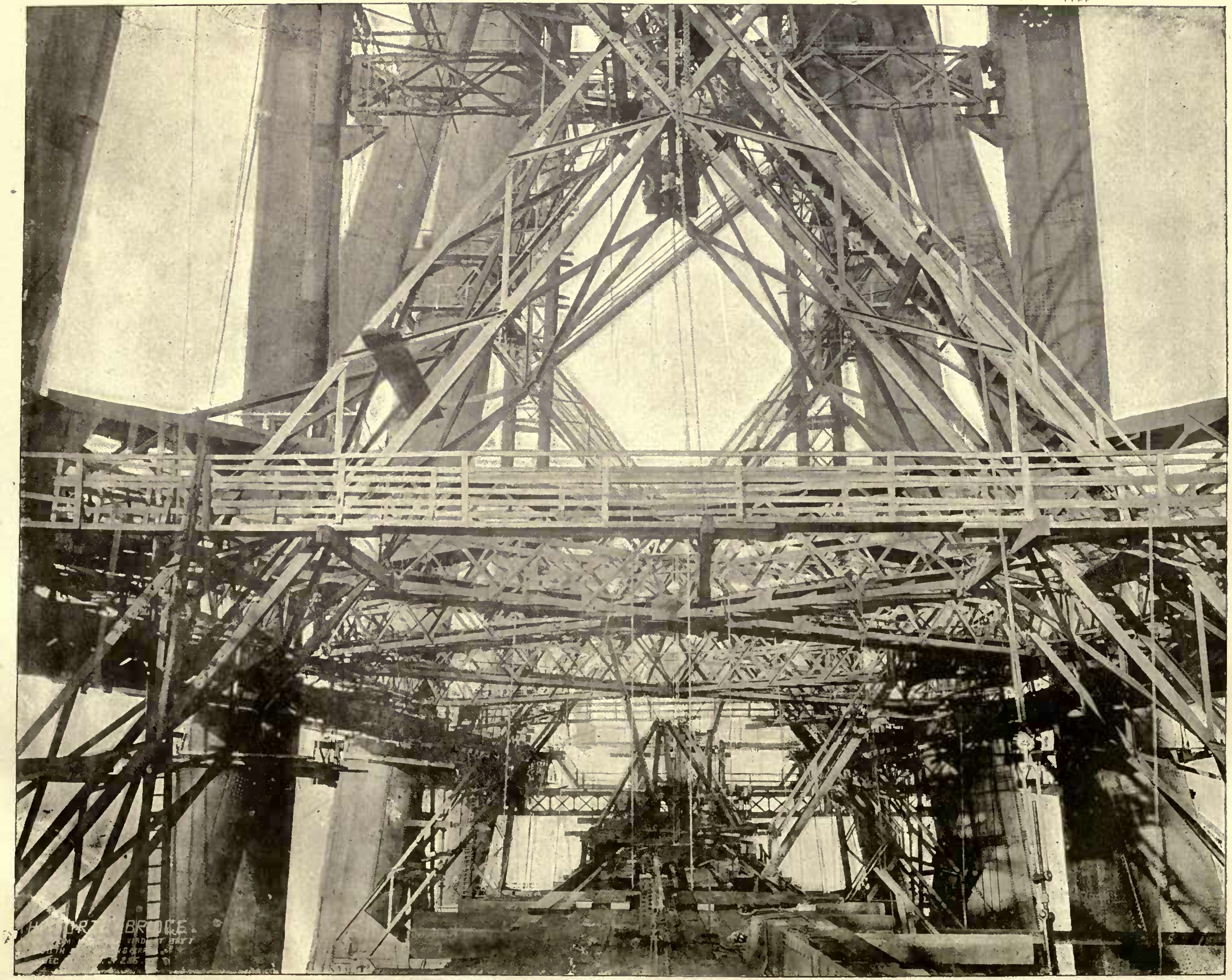


FIFE PIER. FIRST HALF-BAY IN FIXED CANTILEVER, SHOWING LIFTING PLATFORM FOR BUILDING THE LOWER PORTION OF BAY AND TOP MEMBER CRANE WITH PLATFORM SUSPENDED FROM IT.

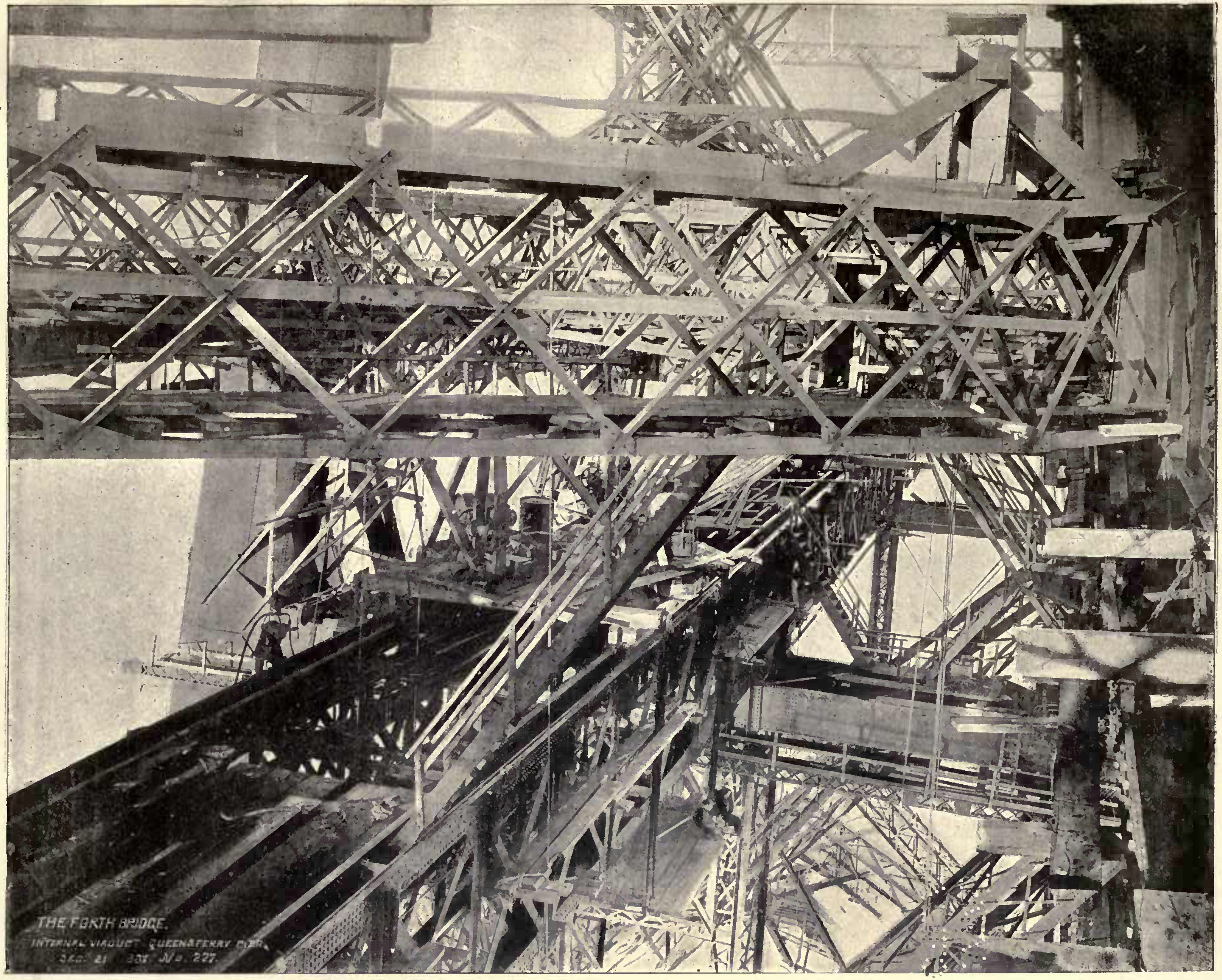
H BRIDGE.

MAKING GOOD A CROSSING BETWEEN STRUTS AND TIES IN FIRST BAY OF CANTILEVERS.

THE FORTH BRIDGE.



CENTRAL TOWER, QUEENSFERRY PIER; HORIZONTAL AND DIAGONAL BRACING GIRDERS; PART OF INTERNAL VIADUCT AND TEMPORARY STAGING.



QUEENSFERRY PIER. INTERNAL VIADUCT FROM CENTRE OF BAY TO WITHIN CENTRAL TOWERS.

FIFE PIER. LOWER HALF OF FIRST BAY IN FIXED CANTILEVER.

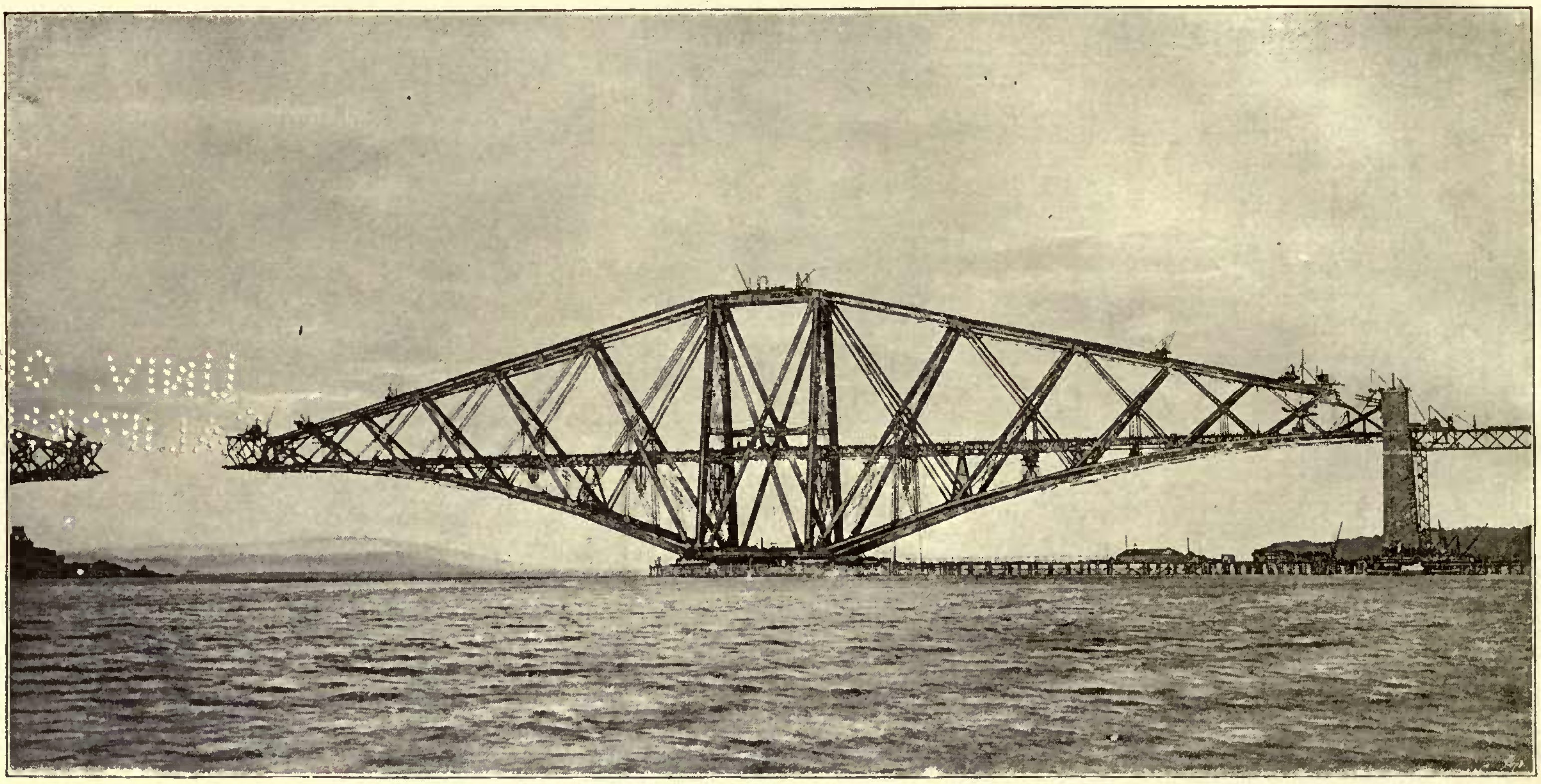
H BRIDGE.

FIFE PIER. CENTRAL TOWER AND LOWER HALF OF FIRST BAY IN FREE CANTILEVER.

FIFE PIER. FREE CANTILEVER COMPLETED AND CENTRAL GIR

H BRIDGE.

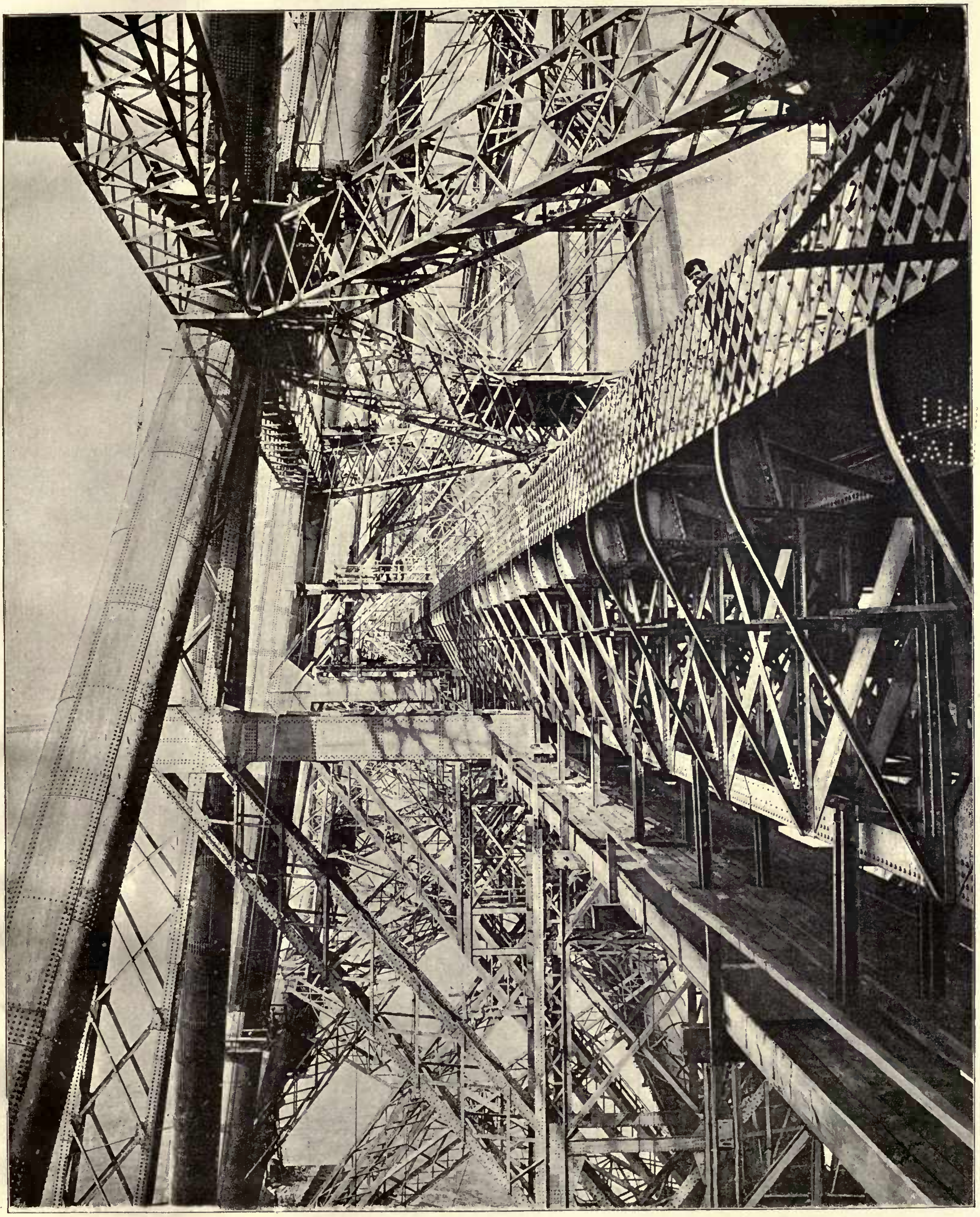
R COMMENCED ; FIXED CANTILEVER NOT QUITE COMPLETED.



QUEENSFERRY PIER AND INCHGARVIE SOUTH CANTILEVER, WITH PARTS OF CENTRAL GIRDER BUILT OUT.

INCHGARVIE SOUTH CANTILEVER, WITH FIRST BAY OF CENTRAL GIRDER BUILT OUT.

IH BRIDGE.



CENTRAL TOWER OF INCHGARVIE; INTERNAL VIADUCT GIRDERS AND WIND FENCE.